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Martinson

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(54) **GUIDING COMPUTATIONAL PERCEPTION THROUGH A SHARED AUDITORY SPACE**

(71) Applicant: **TOYOTA JIDOSHA KABUSHIKI KAISHA**, Toyota-shi, Aichi-ken (JP)

(72) Inventor: **Eric Martinson**, Mountain View, CA (US)

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G10L 25/06 (2013.01)
A61B 5/00 (2006.01)

(52) **U.S. Cl.**
CPC *A61B 5/7405* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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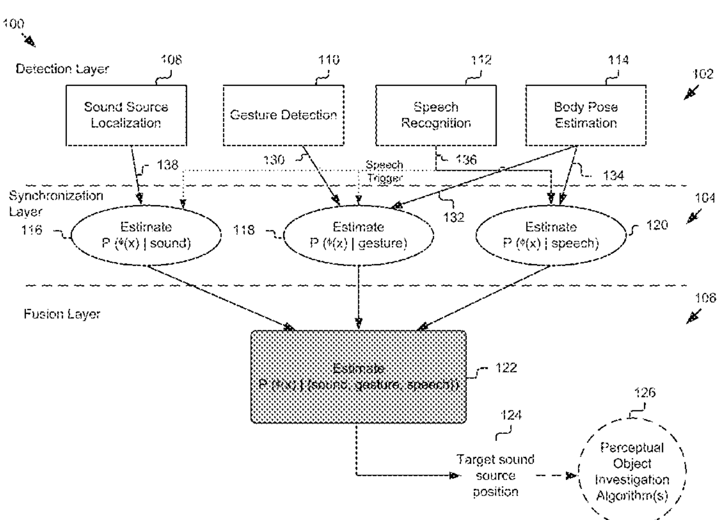
Primary Examiner — Marcus T Riley
(74) *Attorney, Agent, or Firm* — Patent Law Works LLP

(57) **ABSTRACT**

In an example, a computer-implemented method receives one or more user inputs and captures a sound associated with a sound source via one or more capturing devices using sound source localization. The method then estimates one or more first posterior likelihoods of one or more positions of the sound source based on the one or more user inputs and a second posterior likelihood of a position of the sound source based on the sound. The method then estimates an overall posterior likelihood of an actual position of the sound source based on 1) the one or more first posterior likelihoods of the one or more positions of the sound source estimated based on the one or more user inputs and 2) the second posterior likelihood of the position of the sound source estimated based on the sound.

27 Claims, 22 Drawing Sheets



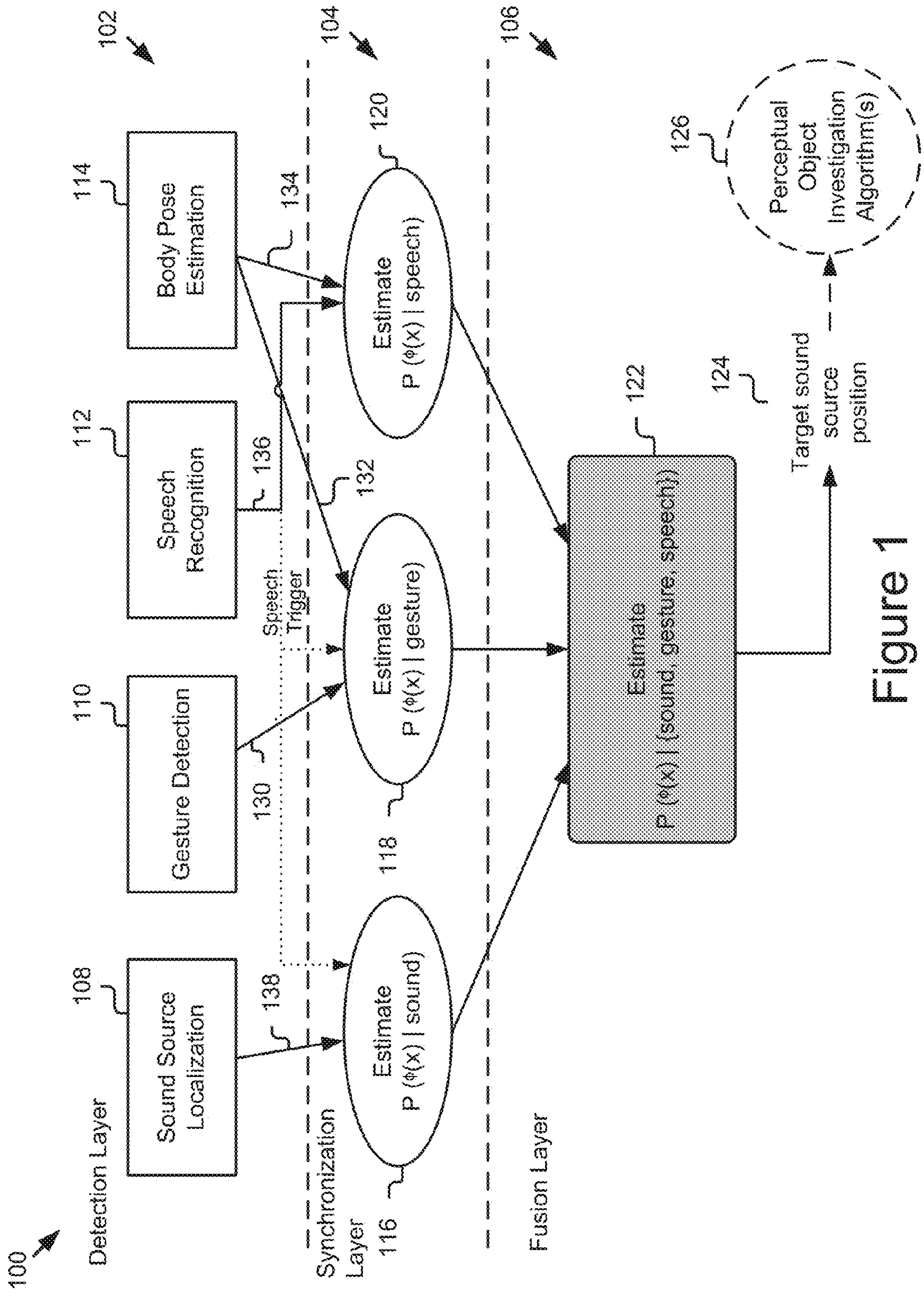

100
Detection Layer
102
108
Sound Source Localization
110
Gesture Detection
112
Speech Recognition
114
Body Pose Estimation
138
130
136
134
132
Speech Trigger
Synchronization Layer
104
116
Estimate P (φ(x) | sound)
118
Estimate P (φ(x) | gesture)
120
Estimate P (φ(x) | speech)
Fusion Layer
106
122
Estimate P (φ(x) | (sound, gesture, speech))
124
Target sound source position
126
Perceptual Object Investigation Algorithm(s)

Figure 1

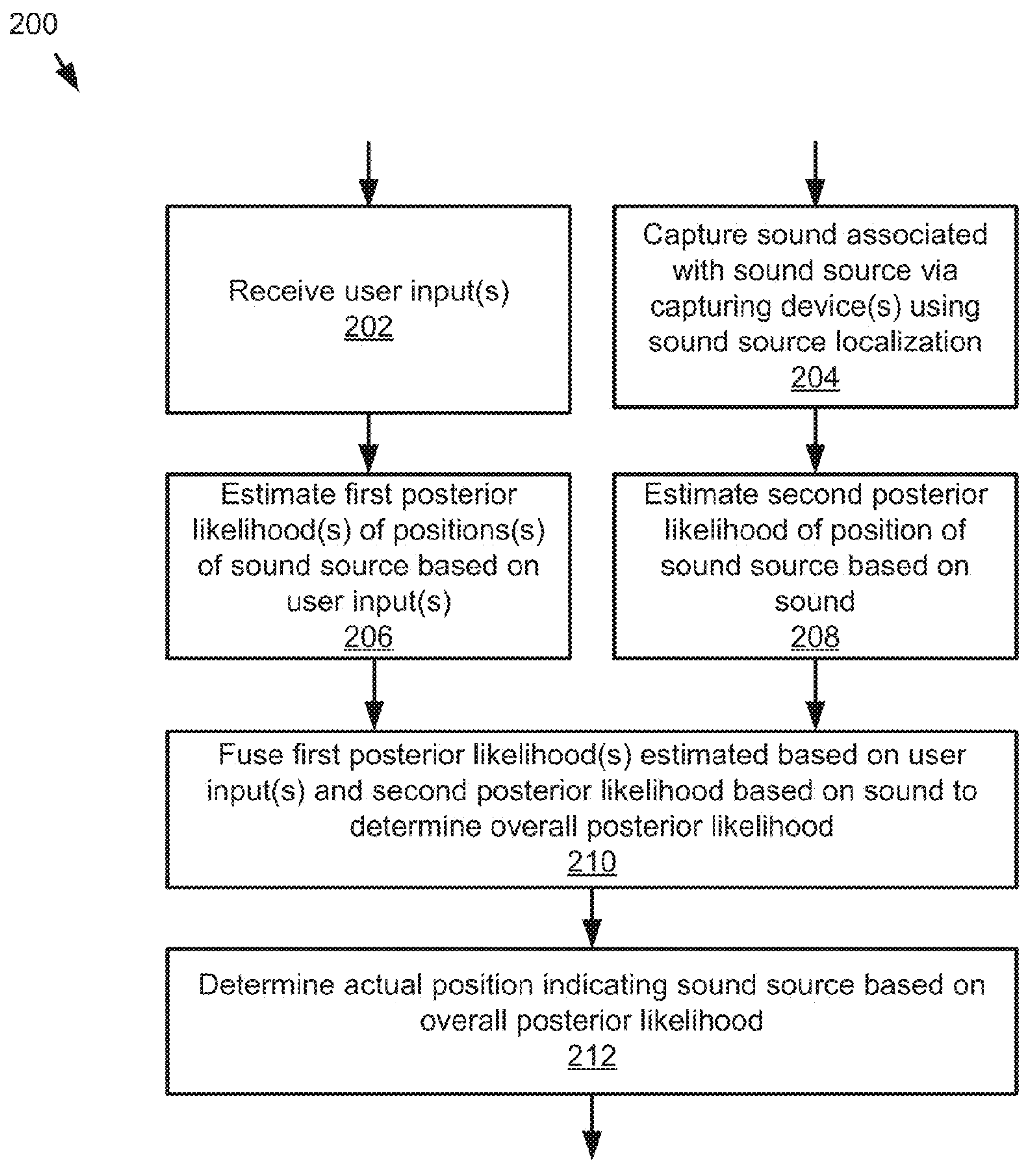

200
Receive user input(s)
202
Capture sound associated with sound source via capturing device(s) using sound source localization
204
Estimate first posterior likelihood(s) of positions(s) of sound source based on user input(s)
206
Estimate second posterior likelihood of position of sound source based on sound
208
Fuse first posterior likelihood(s) estimated based on user input(s) and second posterior likelihood based on sound to determine overall posterior likelihood
210
Determine actual position indicating sound source based on overall posterior likelihood
212

Figure 2

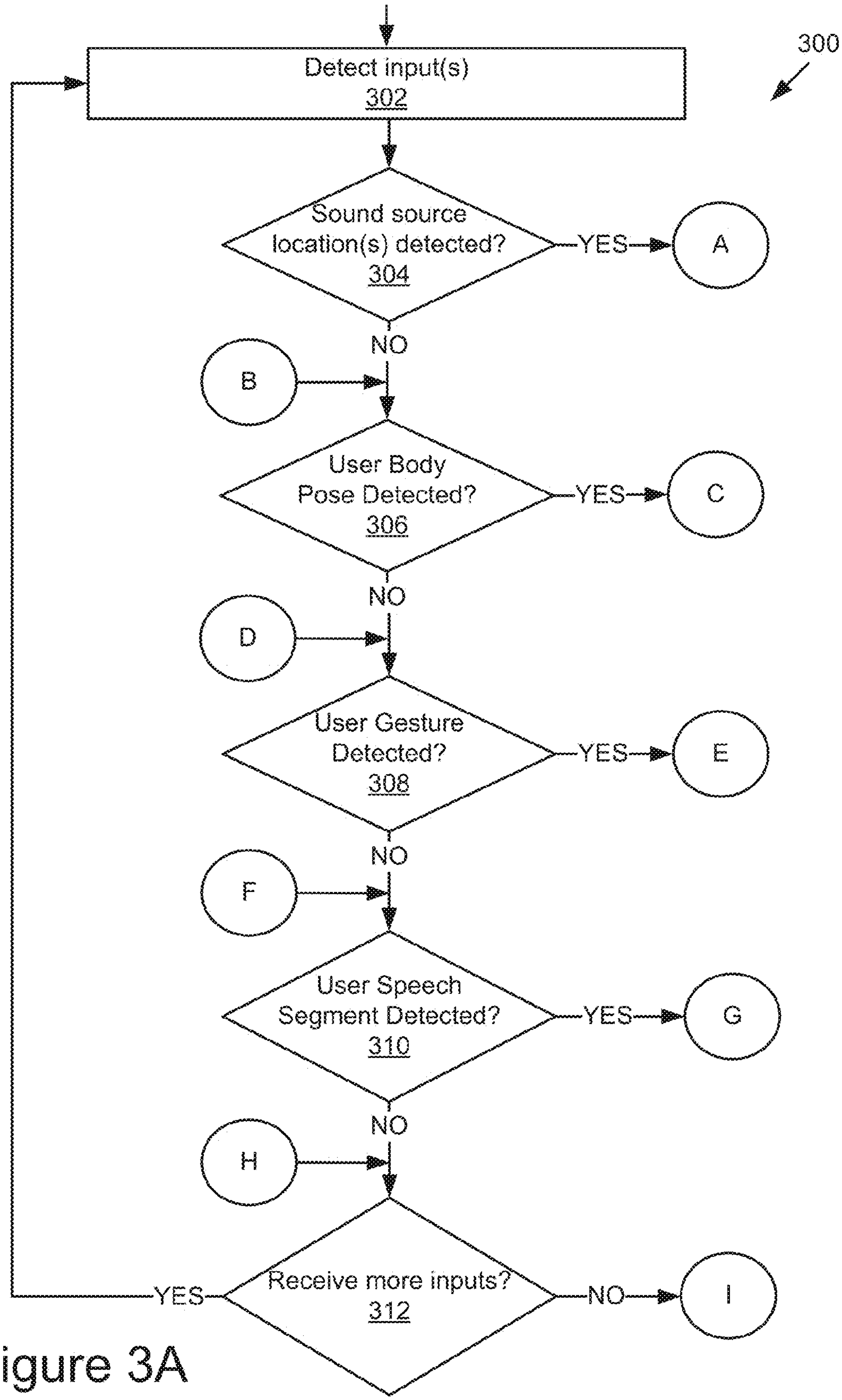

300
Detect input(s)
302
Sound source
location(s) detected?
304
YES
A
NO
B
User Body
Pose Detected?
306
YES
C
NO
D
User Gesture
Detected?
308
YES
E
NO
F
User Speech
Segment Detected?
310
YES
G
NO
H
Receive more inputs?
312
YES
NO
I

Figure 3A

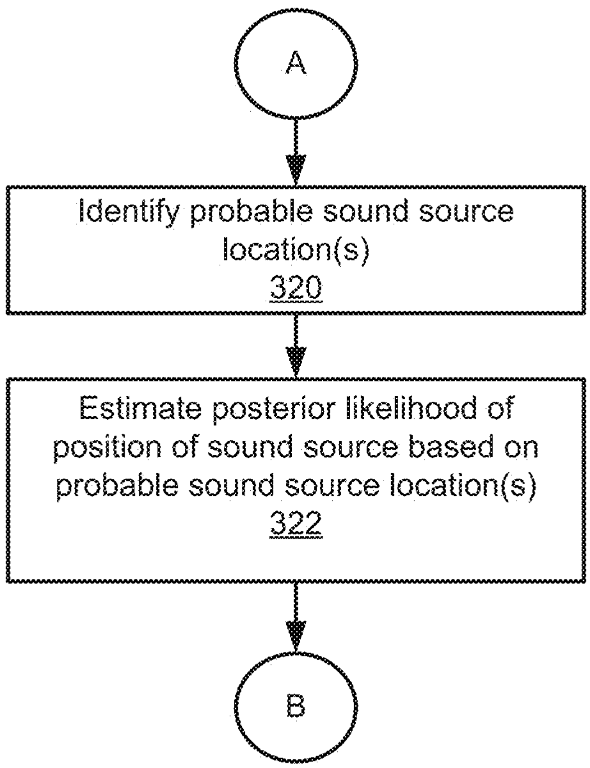

A
Identify probable sound source location(s)
320
Estimate posterior likelihood of position of sound source based on probable sound source location(s)
322
B

Figure 3B

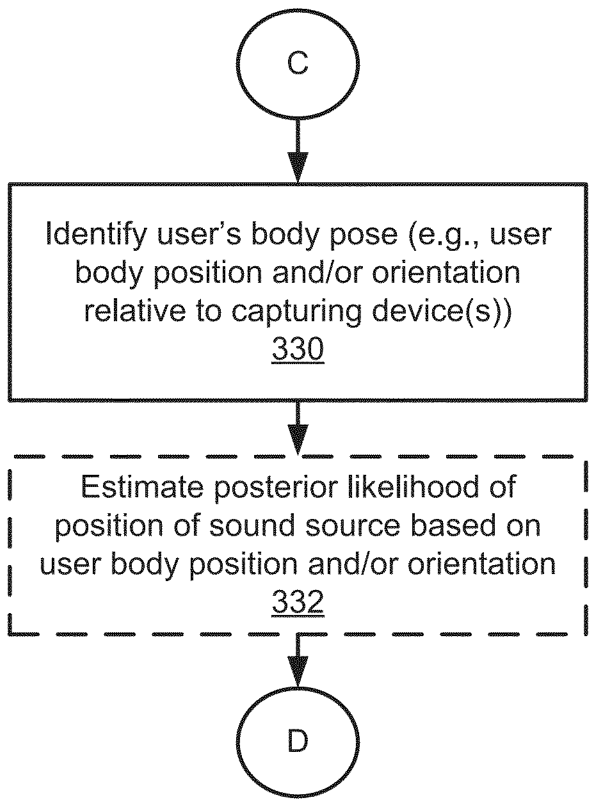

C
Identify user's body pose (e.g., user body position and/or orientation relative to capturing device(s))
330
Estimate posterior likelihood of position of sound source based on user body position and/or orientation
332
D

Figure 3C

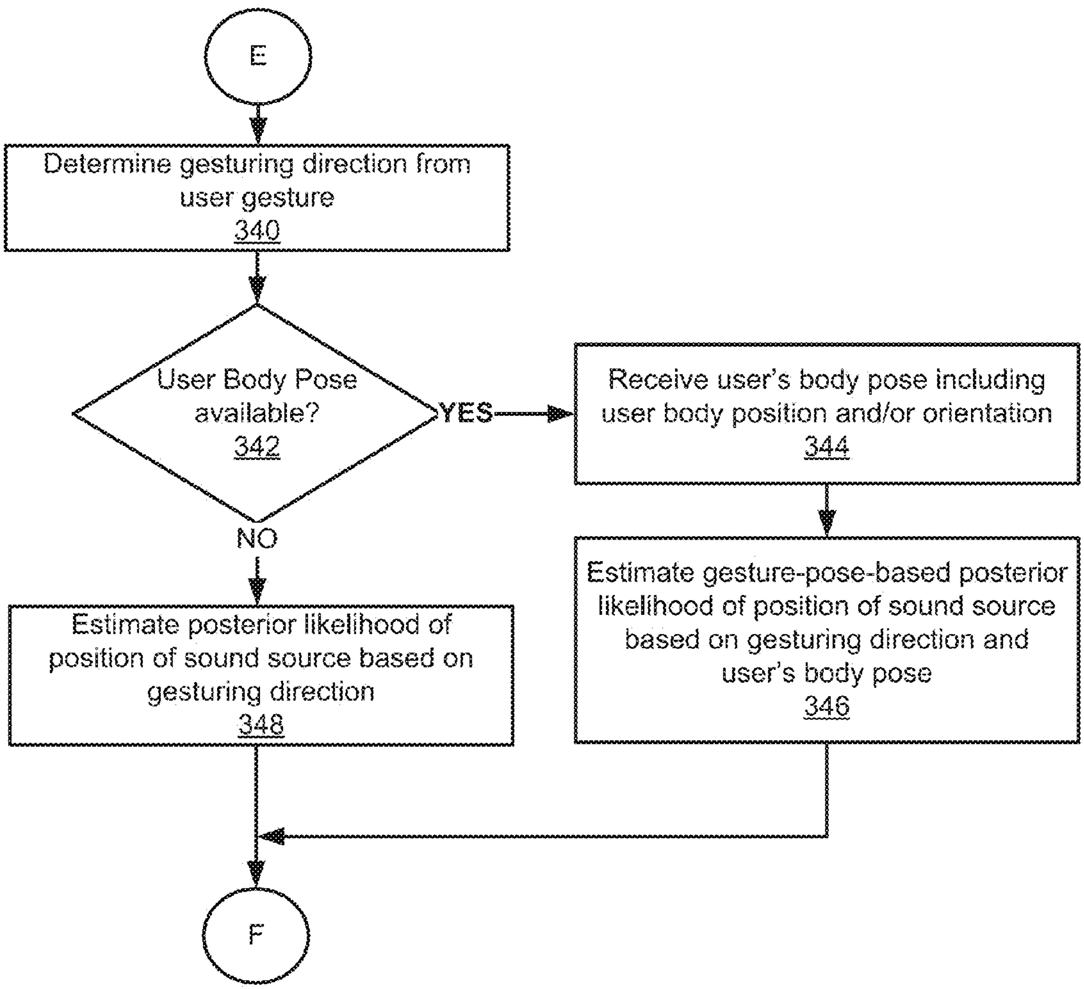

E
Determine gesturing direction from user gesture
340
User Body Pose available?
342
YES
Receive user's body pose including user body position and/or orientation
344
NO
Estimate posterior likelihood of position of sound source based on gesturing direction
348
Estimate gesture-pose-based posterior likelihood of position of sound source based on gesturing direction and user's body pose
346
F

Figure 3D

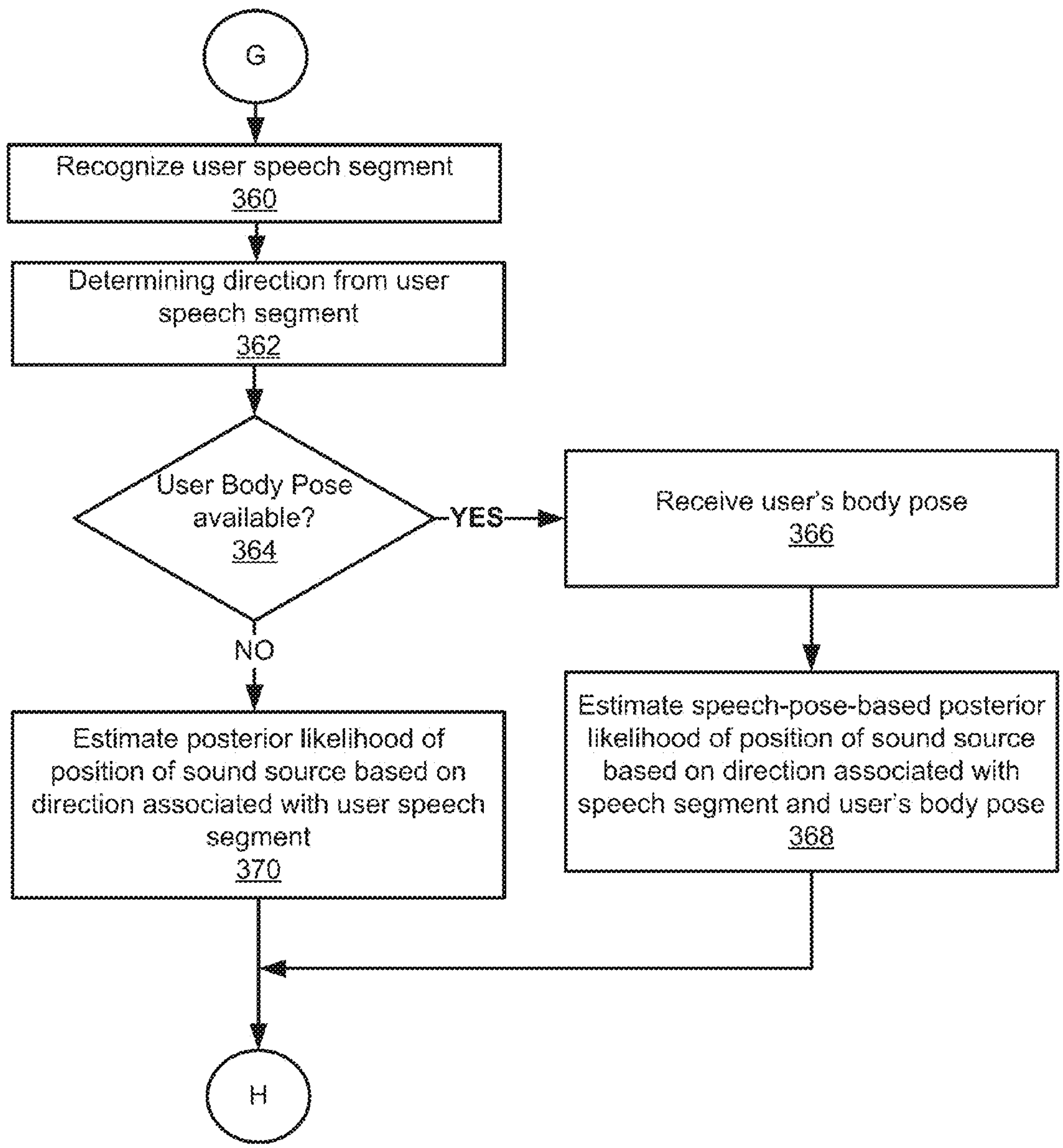

G
Recognize user speech segment
360
Determining direction from user speech segment
362
User Body Pose available?
364
YES
Receive user's body pose
366
NO
Estimate posterior likelihood of position of sound source based on direction associated with user speech segment
370
Estimate speech-pose-based posterior likelihood of position of sound source based on direction associated with speech segment and user's body pose
368
H

Figure 3E

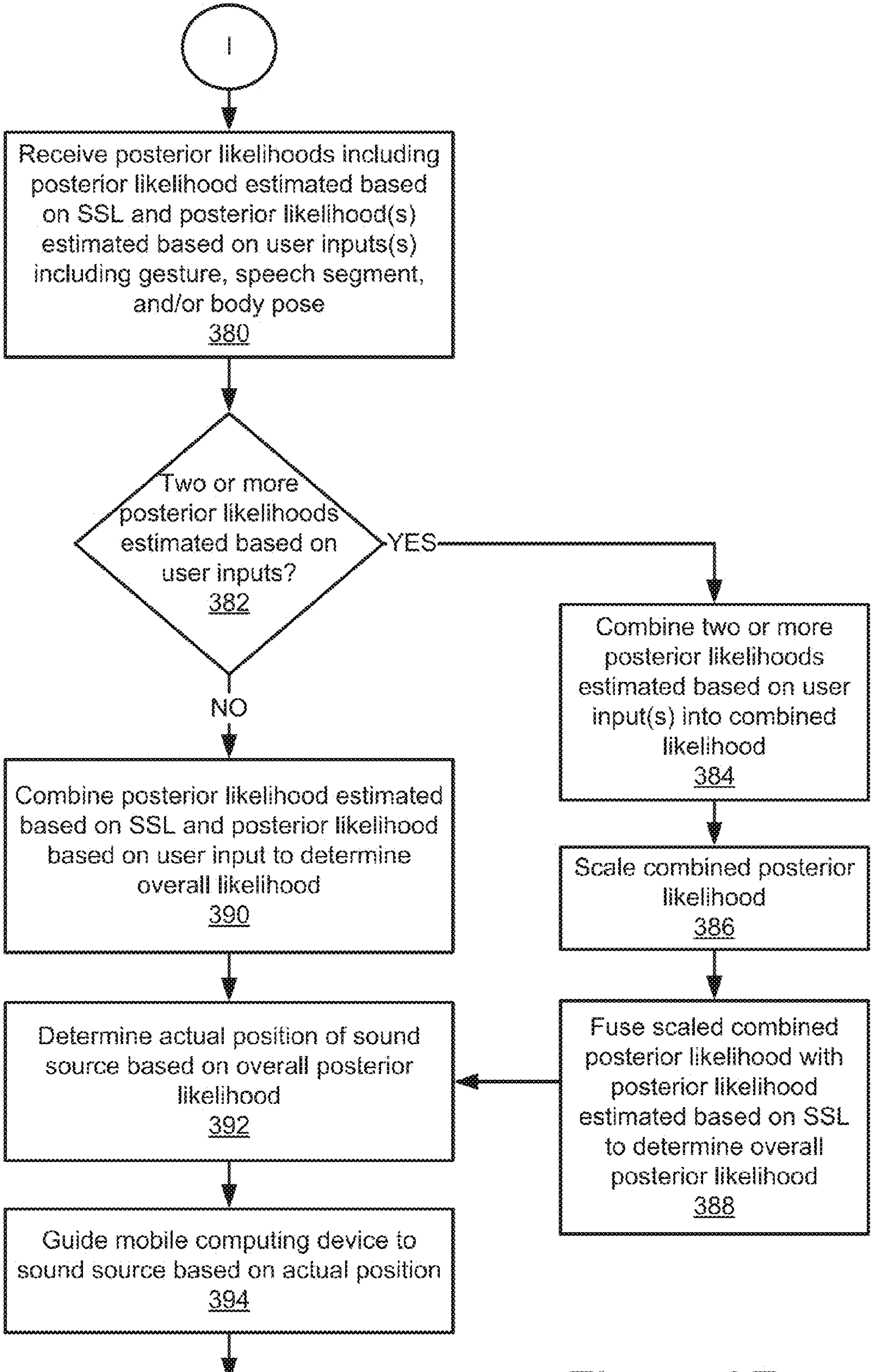

I
Receive posterior likelihoods including posterior likelihood estimated based on SSL and posterior likelihood(s) estimated based on user inputs(s) including gesture, speech segment, and/or body pose
380
Two or more posterior likelihoods estimated based on user inputs?
382
YES
NO
Combine two or more posterior likelihoods estimated based on user input(s) into combined likelihood
384
Scale combined posterior likelihood
386
Fuse scaled combined posterior likelihood with posterior likelihood estimated based on SSL to determine overall posterior likelihood
388
Combine posterior likelihood estimated based on SSL and posterior likelihood based on user input to determine overall likelihood
390
Determine actual position of sound source based on overall posterior likelihood
392
Guide mobile computing device to sound source based on actual position
394

Figure 3F

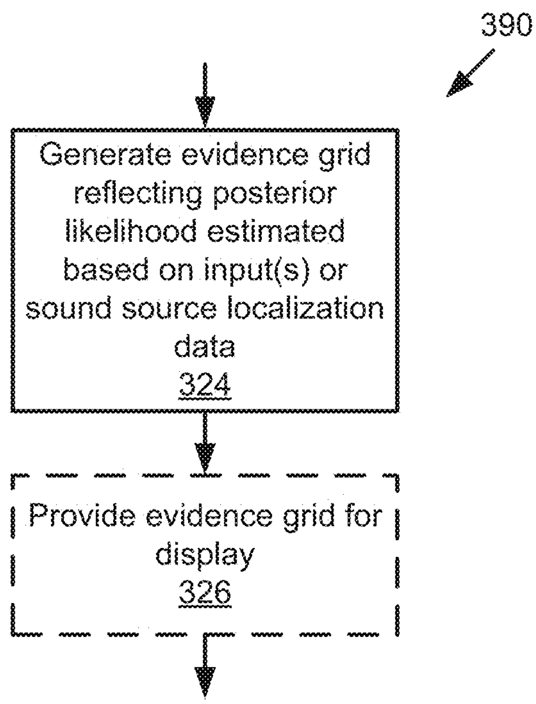
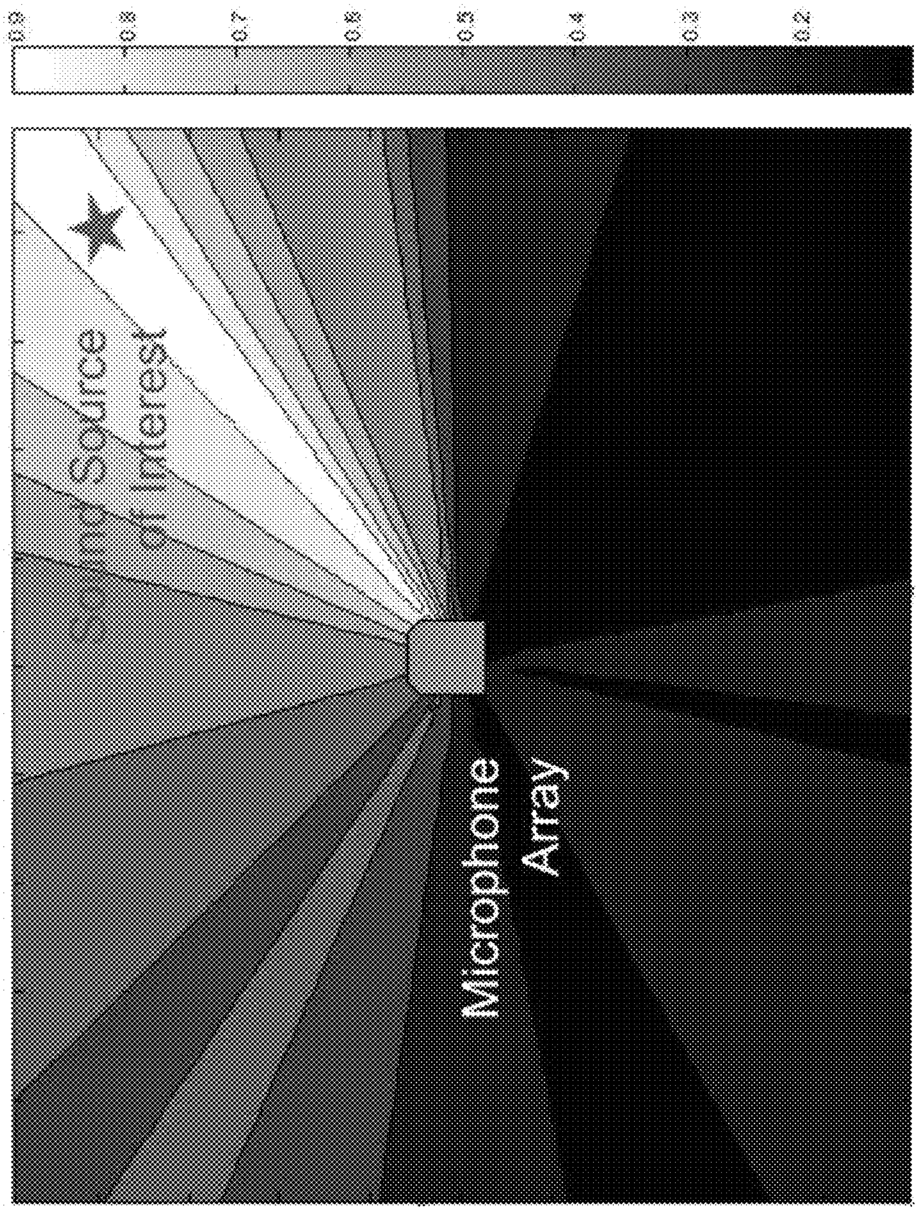

390
Generate evidence grid reflecting posterior likelihood estimated based on input(s) or sound source localization data
324
Provide evidence grid for display
326

Figure 3G

400



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Sound Source of Interest
Microphone Array

Figure 4

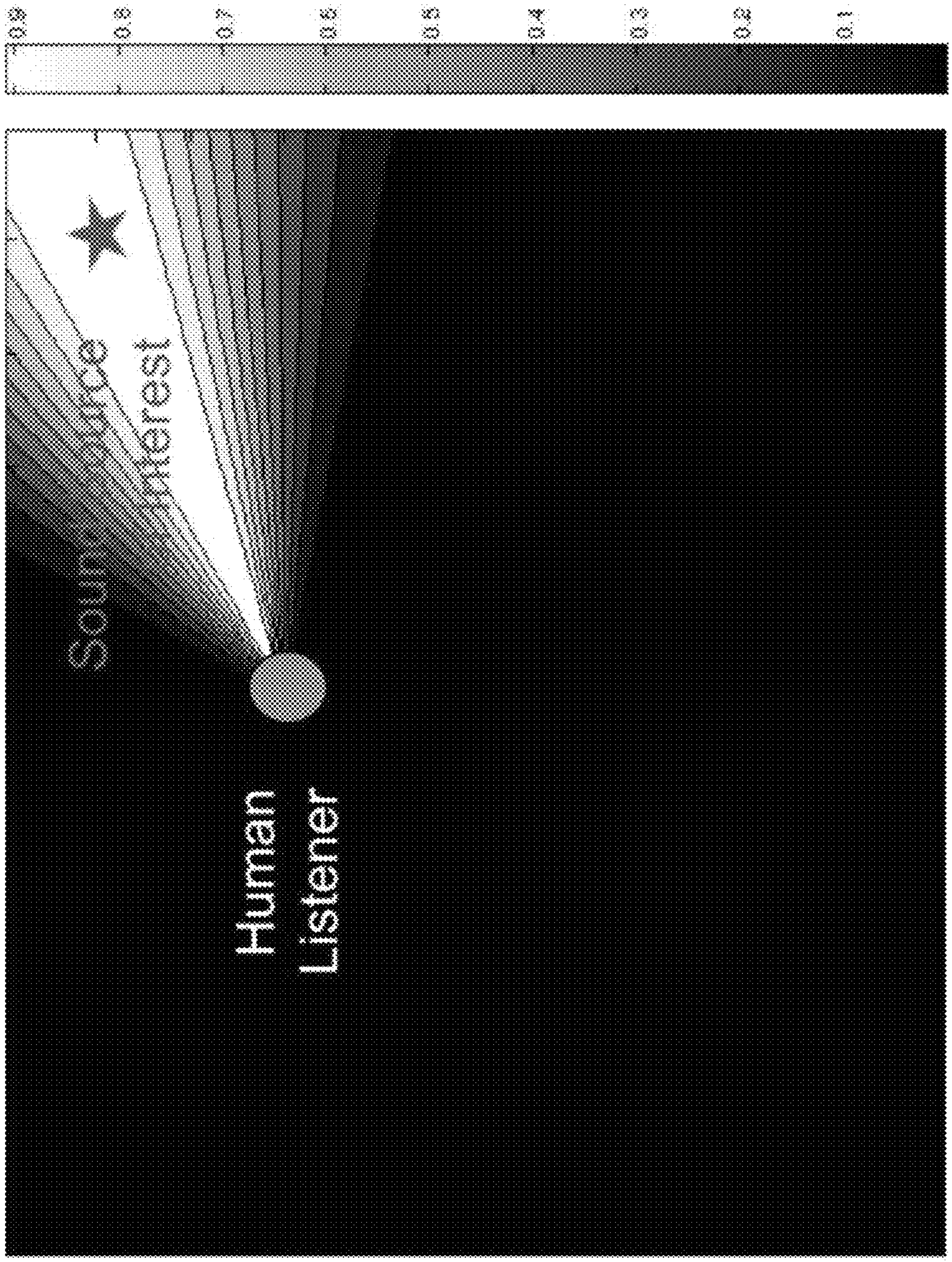
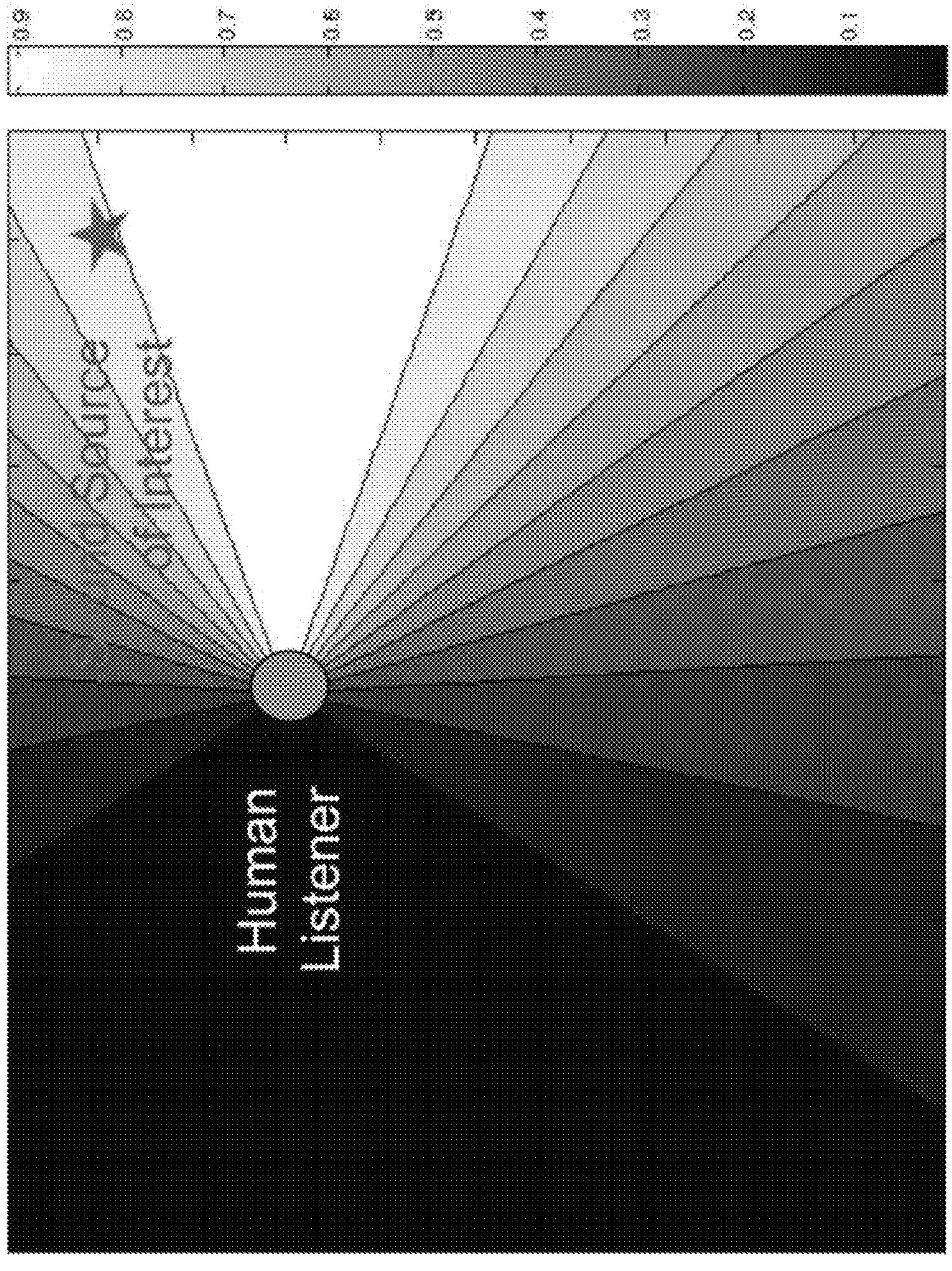


Figure 5

500



600

Figure 6

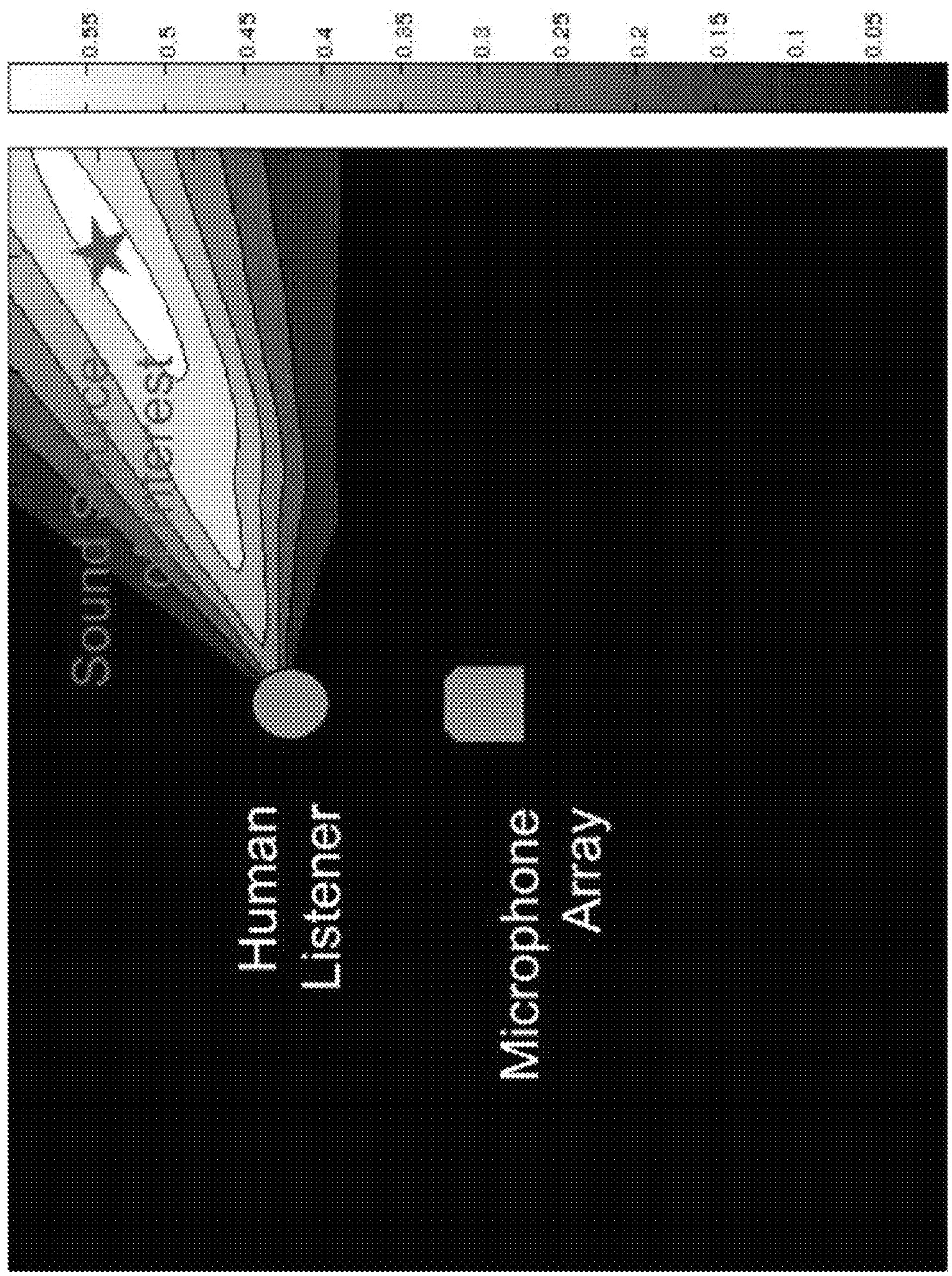

0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Human Listener
Microphone Array

Figure 7

700

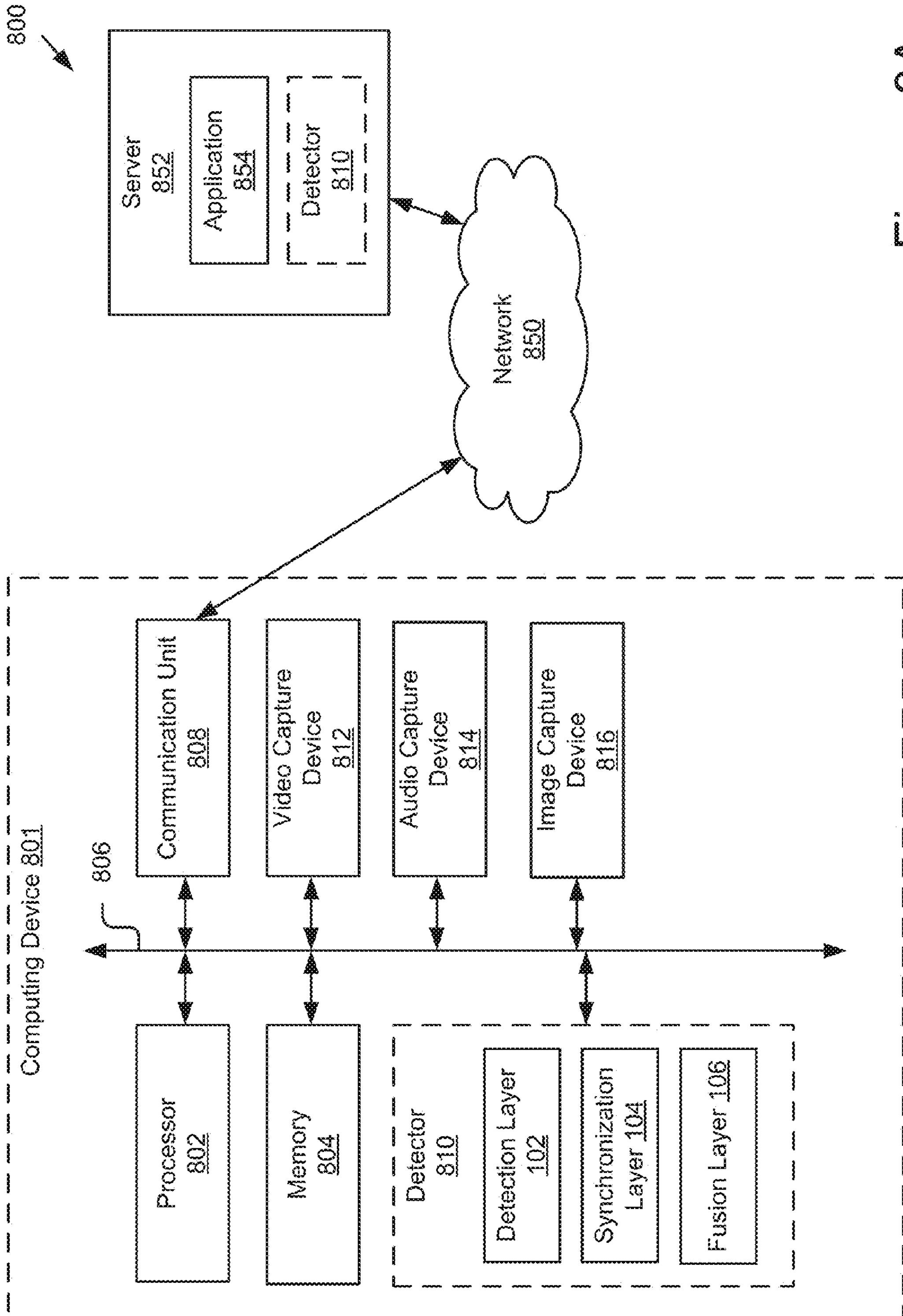

800
Server
852
Application
854
Detector
810
Network
850
Computing Device 801
806
Communication Unit
808
Video Capture
Device
812
Audio Capture
Device
814
Image Capture
Device
816
Processor
802
Memory
804
Detector
810
Detection Layer
102
Synchronization
Layer 104
Fusion Layer 106

Figure 8A

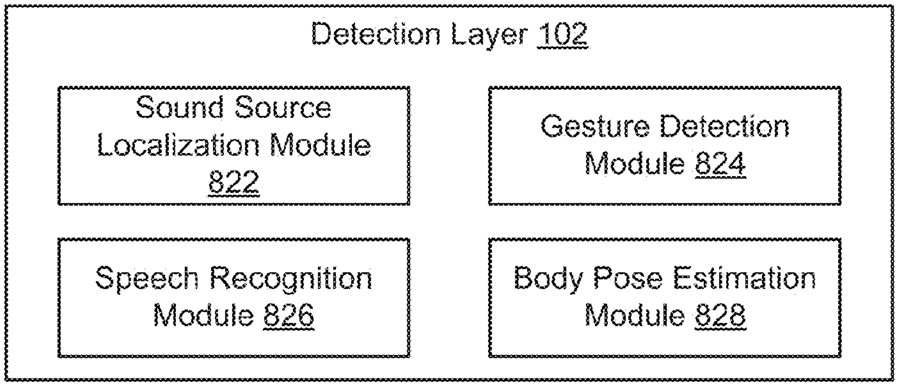


Figure 8B

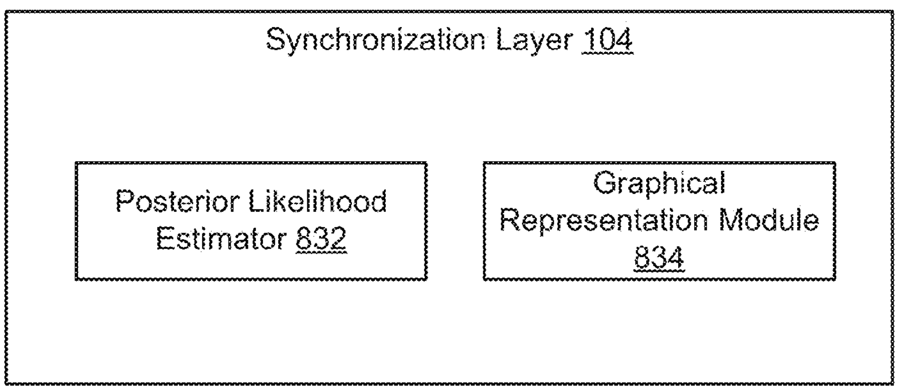


Figure 8C

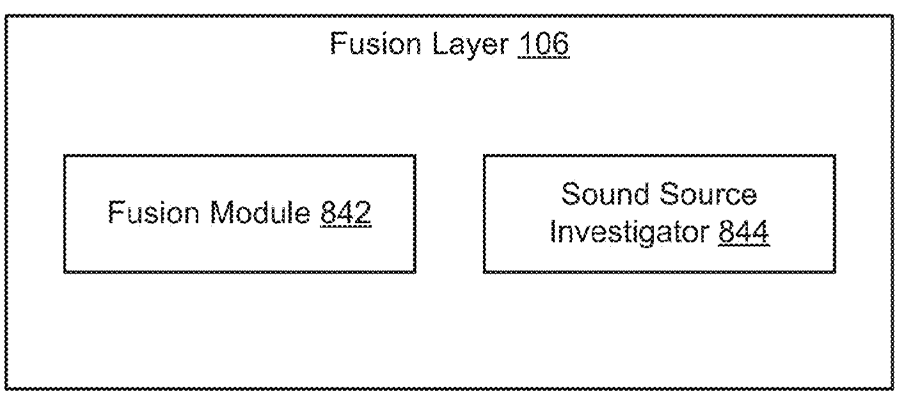


Figure 8D

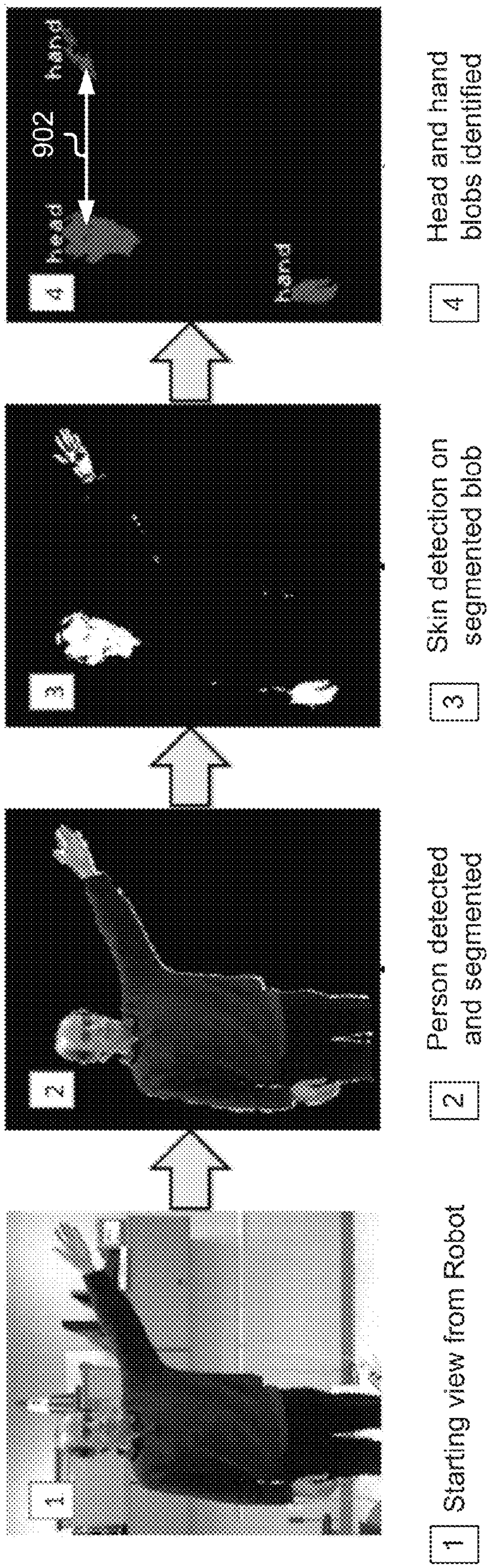

1
Starting view from Robot
2
Person detected and segmented
3
Skin detection on segmented blob
4
head
hand
hand
902
Head and hand blobs identified

Figure 9

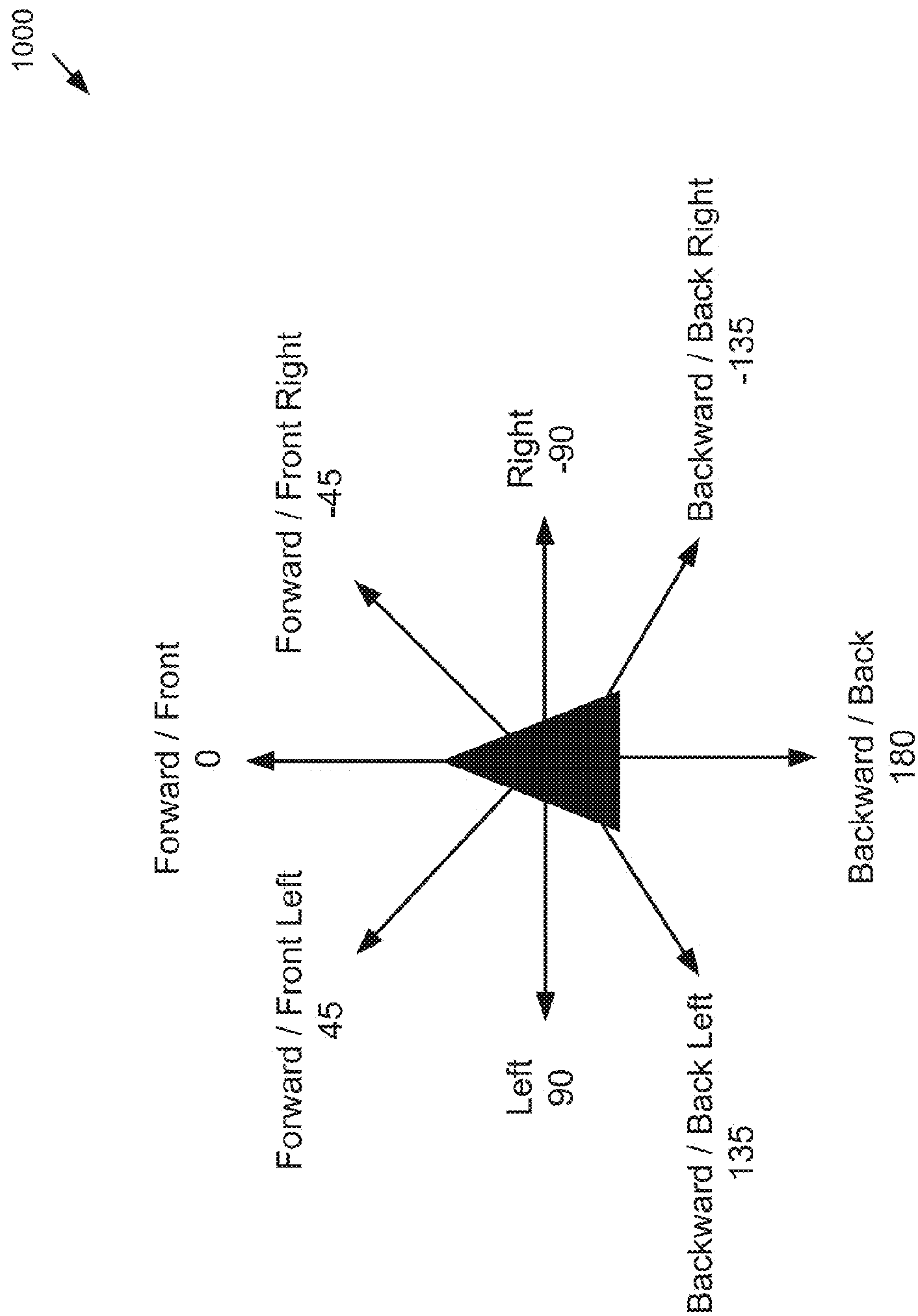

1000
Forward / Front
0
Forward / Front Right
-45
Right
-90
Backward / Back Right
-135
Backward / Back
180
Backward / Back Left
135
Left
90
Forward / Front Left
45

Figure 10

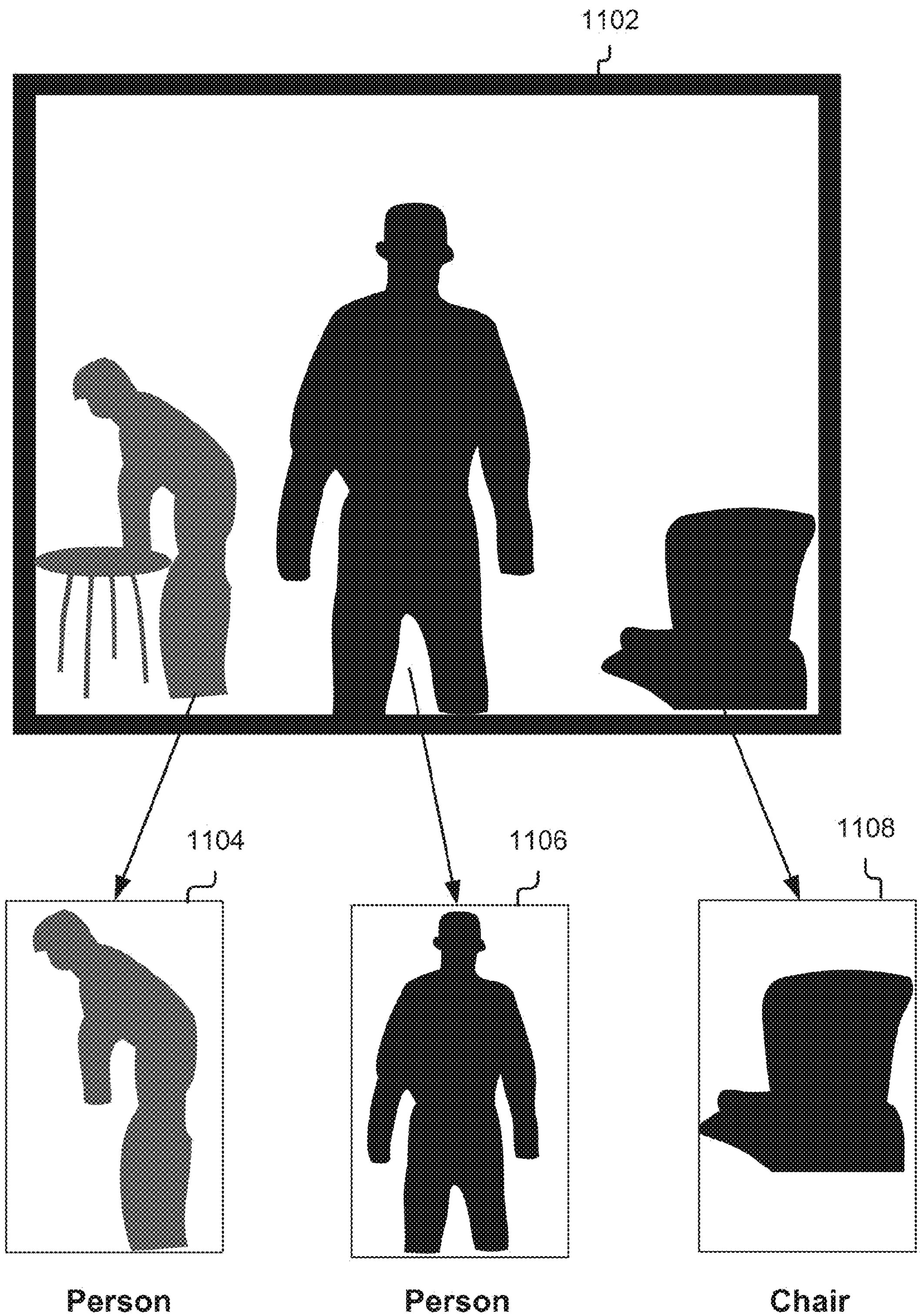


Figure 11

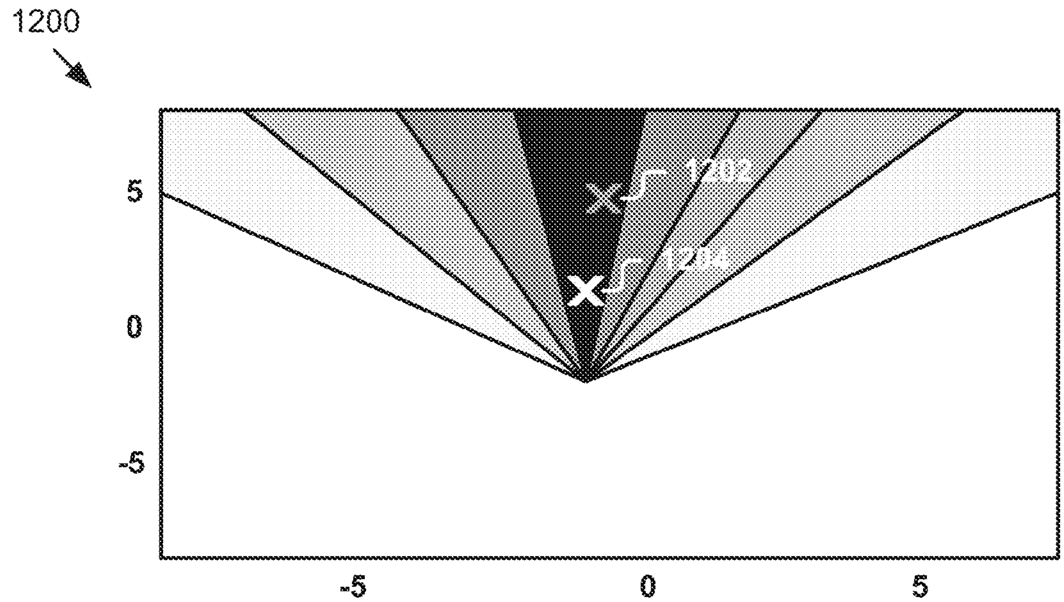


Figure 12A

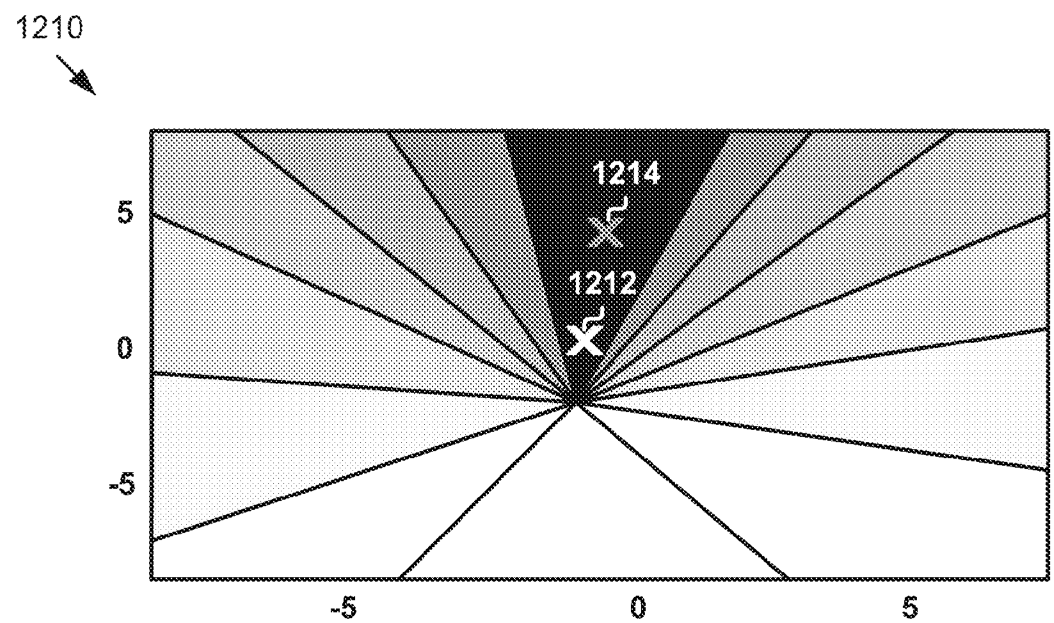


Figure 12B

1220

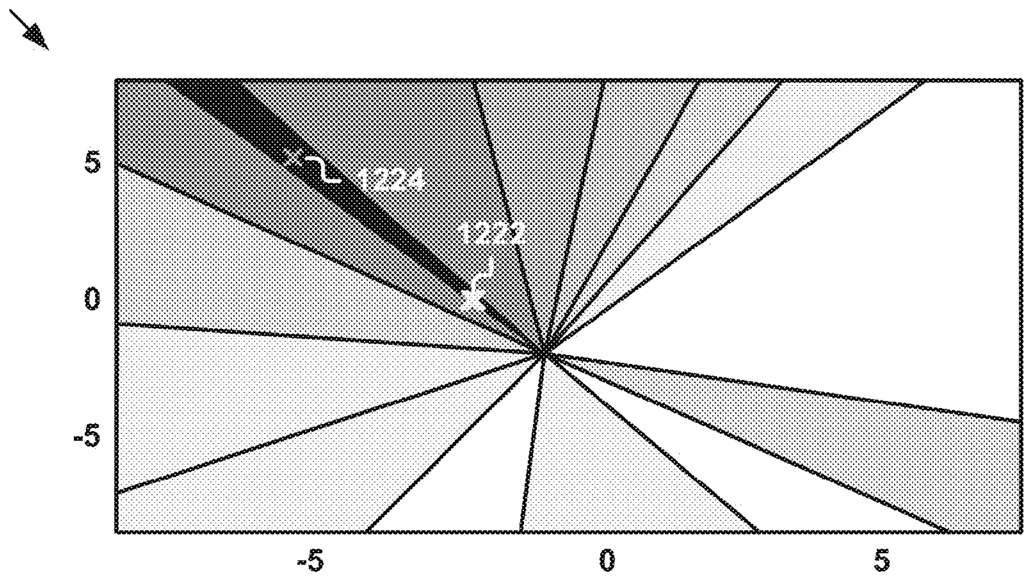


Figure 12C

1230

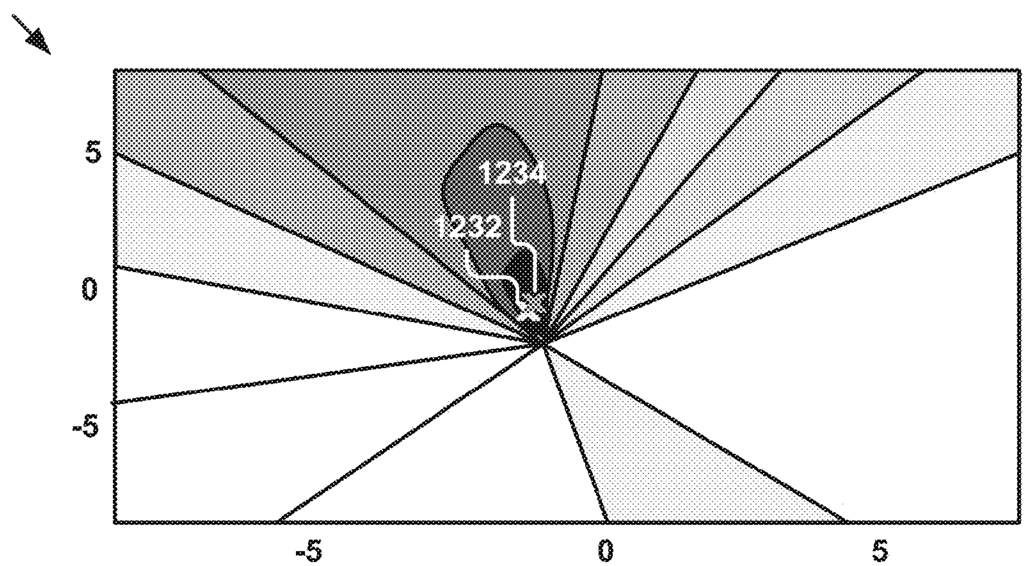


Figure 12D

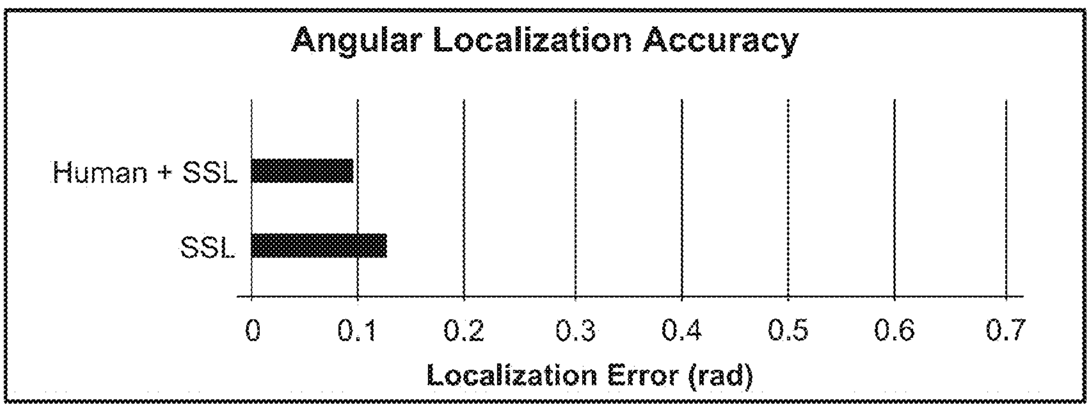

Angular Localization Accuracy
Human + SSL
SSL
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Localization Error (rad)

Figure 13

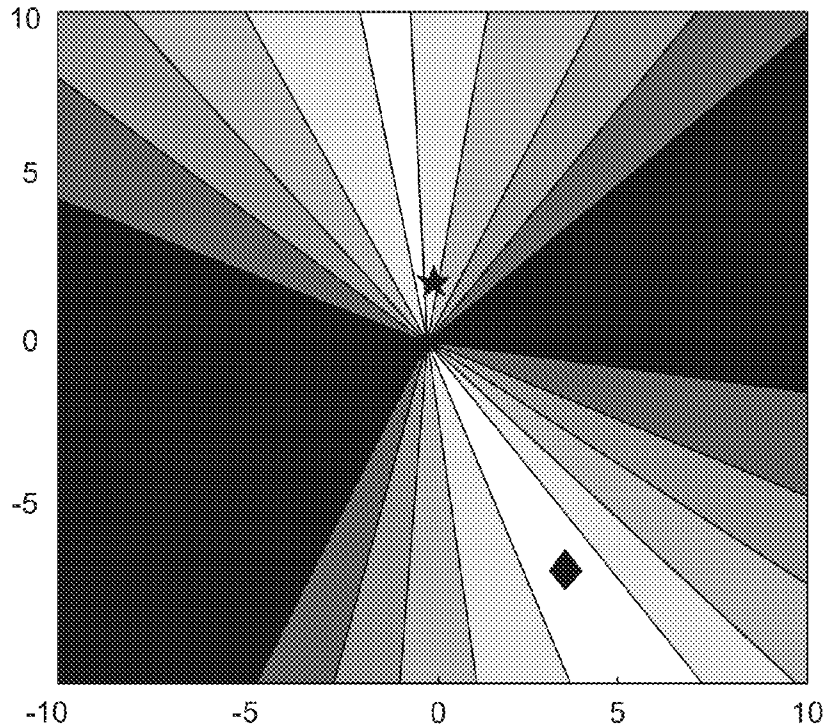


Figure 14A

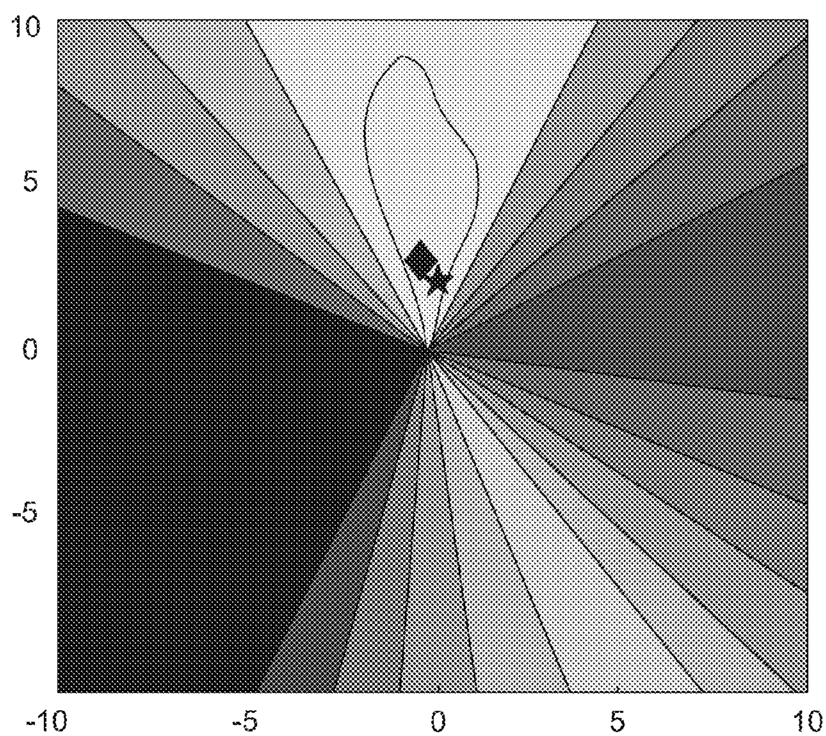


Figure 14B

GUIDING COMPUTATIONAL PERCEPTION THROUGH A SHARED AUDITORY SPACE

BACKGROUND

The specification relates to guiding computational perception through a shared auditory space.

Blindness is an age-related disease. As the world's population continues to get older, the number of blind and visually impaired individuals will likely only increase. These individuals often want to know about what they hear in the world around them. They want to know what other people can "see". Existing systems fail to provide an effective solution that can help these individuals learn about arbitrary objects that they can only hear about, that they do not know the exact location of, or that they do not know uniquely identifiable traits about.

In some cases, guide dogs, which are probably the most well-known aide outside the blind community, are used to help these individuals. However, these dogs are expensive to train, require a lot of work to keep, and are capable of serving these individuals only for a limited number of years. While these guide dogs provide available services, as the blind population grows, providing guide dogs to all these individuals is not realistic.

Today, a robot is capable of watching a lot of objects and/or actions in its surroundings including people, cars, advertisements, etc. Sizable online databases even allow real-time training for computational perception, to create new classifiers on the fly as needed. However, such a robot generally cannot run an endless number of classifiers all the time. It is too computationally intensive, would likely generate too many false positives with even the best of classifiers, and would overwhelm a human user associated with its corresponding system. Some existing robotic solutions have demonstrated how a human can guide the system using gesture or speech and some include robots that are configured to localize sound sources using onboard microphone arrays. However, these solutions generally only utilize what a single agent can detect about an object of interest. For instance, these solutions take into consideration either what a human has detected or what a robot has detected about the object of interest but generally not both. As a result, these solutions often lead to poor accuracy, ambiguity, and can lead to poor guidance for other computational perception systems.

Some existing solutions can find objects of interest in a visual space and then guide a computer vision system to the right target. For audible objects, sound source localization has been used to guide other sensors, but not generally in conjunction with what a human can hear. For instance, in some popular solutions, GPS location is used to query a mobile computer about its surroundings. However, these solutions have difficulty identifying transient sources of noises. In particular, these solutions often fail to query about sources that move or are short in duration because they do not persist long enough to be queried by GPS proximity. Other existing solutions use pointing gestures in Human-Robot interaction to guide a robot to a target in multiple perceptual domains. However, these solutions often generally require a shared visual space between a human and a computer exist and are therefore inflexible. In another solution, multi-array sound source localization is used to identify audible objects. Although this solution can identify auditory objects of interest, it suffers from significant limitations. For instance, this solution assumes that all sensors are microphone arrays having similar capabilities and limitations, which is impractical. In addition, a user using this solution would have to wear additional hardware in order to triangulate accurately on the

source location. Further, the solution accounts for only one type of stimuli, which is often not unique enough to be of interest to a user. As a result, any other sounds that the user might be interested in would have to be pre-specified and trained, which is time consuming and computationally expensive.

SUMMARY

In various embodiments, this specification describes a technology for querying a computing device, such as a robot, about unknown audible objects in a surrounding environment through a combination of computational sound source localization and human inputs including, for instance, pointing gestures and spoken descriptors. According to one innovative aspect of the subject matter described in this specification, a system includes one or more processors and one or more memories storing instructions that, when executed by the one or more processors, cause the system to receive one or more user inputs; capture a sound associated with a sound source via one or more capturing devices using sound source localization; estimate one or more first posterior likelihoods of one or more positions of the sound source based on the one or more user inputs; estimate a second posterior likelihood of a position of the sound source based on the sound; and estimate an overall posterior likelihood of an actual position of the sound source based on 1) the one or more first posterior likelihoods of the one or more positions of the sound source estimated based on the one or more user inputs and 2) the second posterior likelihood of the position of the sound source estimated based on the sound.

In general, another innovative aspect of the subject matter described in this disclosure may be embodied in methods that include receiving, using one or more computing devices, one or more user inputs; capturing, using the one or more computing devices, a sound associated with a sound source via one or more capturing devices using sound source localization; estimating, using the one or more computing devices, one or more first posterior likelihoods of one or more positions of the sound source based on the one or more user inputs; estimating, using the one or more computing devices, a second posterior likelihood of a position of the sound source based on the sound; and estimating, using the one or more computing devices, an overall posterior likelihood of an actual position of the sound source based on 1) the one or more first posterior likelihoods of the one or more positions of the sound source estimated based on the one or more user inputs and 2) the second posterior likelihood of the position of the sound source estimated based on the sound.

Other aspects include corresponding methods, systems, apparatus, and computer program products for these and other innovative aspects.

These and other implementations may each optionally include one or more of the following features and/or operations. For instance, the operations include: fusing, using the one or more computing devices, the one or more first posterior likelihoods of the one or more positions of the sound source and the second posterior likelihood of the position of the sound source to produce the overall posterior likelihood; that the one or more first posterior likelihoods include two or more posterior likelihoods estimated based on two or more user inputs; that fusing the two or more first posterior likelihoods and the second posterior likelihood includes combining, using the one or more computing devices, the two or more first posterior likelihoods into a combined posterior likelihood, scaling, using the one or more computing devices, the combined posterior likelihood, and combining the scaled

combined posterior likelihood with the second posterior likelihood; that the one or more user inputs include a user gesture and a user body pose; that receiving the one or more user inputs further includes determining a gesturing direction from the user gesture and determining one or more of a position and orientation from the user body pose; that estimating the one or more first posterior likelihoods further includes estimating a gesture-pose-based posterior likelihood of a position of the sound source based on the gesturing direction and the one or more of the position and orientation associated with the user body pose; that the one or more inputs include a user speech segment and a user body pose; that receiving the one or more user inputs further includes determining a direction from the user speech segment and determining one or more of a position and orientation from the user body pose; that estimating the one or more first posterior likelihoods further includes estimating a speech-pose-based posterior likelihood of a position of the sound source based on the direction associated with the speech segment and the one or more of the position and orientation associated with the user body pose; that estimating the one or more first posterior likelihoods further includes generating one or more first evidence grids of likely sound source positions based on the one or more user inputs, the one or more first evidence grids reflecting the one or more first posterior likelihoods, respectively; that estimating the second posterior likelihood further includes generating a second evidence grid of likely sound source positions based on the sound, the second evidence grid reflecting the second posterior likelihood; that estimating the overall posterior likelihood of the actual position of the sound source further includes combining the one or more first evidence grids and the second evidence grid; and guiding, using the one or more computing devices, a mobile computing device to the actual position of the sound source. For instance, the features include that the one or more user inputs include one or more of a user gesture, a user speech segment, and a user body pose; and the one or more capturing devices includes one or more of an image capturing device, a video capturing device, and an audio capturing device.

The technology described herein is particularly advantageous in a number of respects. For example, the technology can improve the ability of a user, such as a blind or visually impaired individual, to ask directed queries about the environment around them; can limit the search space and generate better targeted information; use sound as a shared medium, which is a natural interface for the blind individual, as compared to other approaches requiring a shared visual space; and can incorporate human gestures and speech in auditory localization, which eliminates the need for on-body hardware. It should be understood that the foregoing advantages are provided by way of example and the technology may have numerous other advantages and benefits.

The disclosure is illustrated by way of example, and not by way of limitation in the figures of the accompanying drawings in which like reference numerals are used to refer to similar elements.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram illustrating an example shared auditory perception architecture.

FIG. **2** is a flowchart of an example method for determining a position of a sound source of interest based on sound source localization and user inputs.

FIG. **3**A-**3**G are flowcharts of example methods for determining a position of a sound source of interest based on sound source localization and various user inputs.

FIG. **4** is a graphical representation illustrating an example posterior likelihood estimate determined based on a set of time delay on arrival measurements from a microphone array.

FIG. **5** is a graphical representation illustrating an example posterior likelihood estimate determined based on a user pointing gesture.

FIG. **6** is a graphical representation illustrating an example posterior likelihood estimate determined based on a user speech segment.

FIG. **7** is a graphical representation illustrating an example posterior likelihood estimate determined based on the combination of computational sound source localization and one or more user inputs.

FIG. **8**A is a block diagram illustrating an example system architecture.

FIG. **8**B is a block diagram of an example detection layer.

FIG. **8**C is a block diagram of an example synchronization layer.

FIG. **8**D is a block diagram of an example fusion layer.

FIG. **9** is an example process for detecting a user pointing direction.

FIG. **10** depicts directions and angles associated with a set of user speech commands.

FIG. **11** is a graphical representation illustrating person detection from a depth image.

FIGS. **12**A-**12**D are evidence grids representing posterior likelihoods estimated based on a user pointing direction, user speech, computational sound source localization, and a combination of the foregoing.

FIG. **13** is an example graph illustrating average angular localization error associated with various sound source detection components in an example scenario.

FIG. **14**A depicts a sound source location estimation using only computation sound source localization given multiple sound sources present in an environment.

FIG. **14**B depicts a sound source location estimation using a combination of computation sound source localization and one or more user inputs given multiple sound sources present in an environment.

DETAILED DESCRIPTION

According to some embodiments, the technology described in this specification makes use of a shared auditory space, using both what a computer can hear and what a person can hear, to locate a sound source and guide a mobile computing device such as a robot equipped with visual sensors, to the sound source. More specifically, in one example, the technology can detect and convert verbal (e.g. speech) and/or non-verbal (e.g. gestural) cues localizing a sound source of interest into probabilistic representations of sound source likelihoods, referred to herein in some embodiments as first posterior likelihoods. The technology can then fuse the first posterior likelihoods with a second posterior likelihood computed by the technology using computational sound source localization (SSL) estimated on real-time microphone array data. The technology can then find a position that maximizes the fused likelihood to distinguish the sound source of interest from other sounds in an environment. That position can then be used to guide a mobile computing device such as a robot to the sound source of interest or for other purposes.

System Overview

FIG. **1** illustrates a block diagram of an example shared auditory perception architecture **100**. The illustrated architecture **100** has three layers including a detection layer **102**, a synchronization layer **104**, and a fusion layer **106**. The detection layer **102** includes four distinct perceptual components: sound source localization **108**, gesture detection **110**, speech recognition **112**, and body pose estimation **114**, each of which are described in more detail below.

Sound Source Localization **108**

Utilizing one or more capturing devices, such as a microphone array, a sound source localization module **822** (e.g., see FIG. **8**B) may identify probable sound source locations, such as directions, Cartesian positions, etc. In some embodiments, the one or more capturing devices may localize sound sources by determining differences between signals arriving at capturing devices (e.g., different microphones in the array) and comparing them to the physics of in-air sound propagation.

In some embodiments, the sound source localization module **822** may use an implementation of the machine listening toolbox (HARK) and the MUSIC (MUltiple SIgnal Classification) algorithm for SSL, although other approaches may also be used. In some embodiments, the sound source localization module **822** may combine the MUSIC algorithm with a tracking algorithm to filter localization angles and assign an ID to a sound source. The sound source localization module **822** may require, in some instances, a pre-specified number of sound sources be determined prior to identifying the sound source locations. In some embodiments, to allow for the possibility that a sound source of interest is not the loudest and/or worst sound in an environment, the number of sound sources being detected and tracked may be set to a certain number, such as two.

Gesture Detection **110**

The gesture detection module **824** (e.g., see FIG. **8**B) may receive sensor data and process it to determine a user gesture. A user gesture includes a motion made by a body part of the user indicating a direction or action. Gestures may be captured by one or more sensors, such as depth-based skeletal tracking systems, range-based arm detection systems, and/or visual detection in RGB-D images.

In some embodiments, the gesture detection module **824** performs hand detection and gesture recognition. For instance, the gesture detection module **824** may use a multi-level approach involving 3D and 2D data for hand detection and gesture recognition. The gesture detection module **824** may capture 3D depth information along with 2D color texture maps via the one or more sensors. The 3D depth information may first be processed to reliably segment human body (e.g., upper) blobs. For instance, as depicted in FIG. **9**, the gesture detection module **824** may process a depth image recorded from the one or more sensors to identify blob(s) and may analyze the blob(s) to validate them as depicting human body. Next, the gesture detection module **824** may perform color segmentation on the 2D color texture maps or image regions corresponding to each blob segmented in the 3D depth information to detect human skin tones. In some embodiments, the gesture detection module **824** may perform skin tone segmentation using HSV color space having the following thresholds:

$$0° < H < 25° \text{ or } 335° < H < 360°,$$

$$0.2 < S < 0.6,$$

$$V \geq 40.$$

The result produced by the skin tone detection performed by the gesture detection module **824** on each of the segmented human body blobs may include a subset of blobs corresponding to the face and one or more hands of the person associated with the body blob. In some instances, one or both of the hands might be occluded due to position of the person in the scene or simply because the person's hands were not captured to begin with. The gesture detection module **824** may track the blobs corresponding to the face and hands independently, and use face detection, in parallel, to identify which blob belongs to the face. In some embodiments, upon identifying one of skin colored blobs as belonging to the face, the gesture detection module **824** may identify remaining blobs as hands.

In some embodiments, the gesture detection module **824** may identify a direction in which a user is pointing by determining a line from a point (e.g., from the center) of a face blob to a point (e.g., to the center) of a hand blob. For example, as shown in FIG. **9**, the gesture detection module **824** may use the line **902** to determine that the person is pointing in the left direction.

Speech Recognition **112**

A user may use speech as a natural way of conveying a direction to a computing device (e.g., a robot, computer, etc.). In some embodiments, the user speech may be used to estimate a location of the sound source of interest. For instance, a user may indicate the location of the sound source to the computing device using a speech segment. The speech recognition module **826** (e.g., see FIG. **8**B) may be capable of recognizing one or more user speech segments. A user speech segment may include a word, phrase, or command spoken by the user. In some instances, the speech segment may be directed by the user at a computing device, such as a robot. The one or more user speech segments may include one or more key orientation descriptors such as "left", "right", "forward", "backward", "up", and "down" that indicate direction to the source of interest in a human coordinate frame. FIG. **10** depicts an example direction and angle associated with each of the one or more key orientation descriptors. In some further examples, the speech segment may be provided in conjunction with a user gesture. For instance, the user might say, "it's over there" while simultaneously pointing in a particular direction.

Body Pose Estimation **114**

The body pose estimation module **828** (e.g., see FIG. **8**B) may detect a person following a robot and identify that person's body pose (e.g., position and/or orientation). In some embodiments, the body pose may be estimated relative to the one or more sensors (e.g., a microphone array). In some embodiments, a body pose including the user's body position and/or orientation may be combined by the body pose estimation module **828** with the user's gestured direction and/or the user's speech segment to determine a combined posterior likelihood of the sound source of interest as described below with reference to the synchronization layer **104**.

In some embodiments, the body pose estimation module **828** may detect people in in depth images using a layered approach. In this approach, the body pose estimation module **828** may search for connected components (e.g., blobs) in a depth image, and then identify segments (e.g., horizontal slices) of those blobs as belonging to people or other objects based on the curvature of the segments. For example, as depicted in FIG. **11**, the body pose estimation module **828** can extract three blobs from a depth image **1102** and then identify each of the blobs as belonging to people **1104** and **1106** and a chair **1108**.

The user's body pose (e.g., the user body position and/or orientation) identified by the body pose estimation module **828** can be used in various embodiments to identify head/arm positions and in combination with the speech recognition results to localize sound sources with speech, as described elsewhere herein.

Synchronization Layer **104**

In the synchronization layer **104**, the posterior likelihood estimator **832** (e.g., see FIG. **8**C) may estimate posterior likelihoods of a sound source using various inputs from the detection layer **102** including from the sound source localization **108**, the gesture detection **110**, the speech recognition **112**, and/or the body pose estimation **114**. In some embodiments, a posterior likelihood may be estimated based on SSL, gesture, speech, and/or body pose. For instance, the posterior likelihood estimator **832** may estimate a posterior likelihood **116** ($P(^{\Phi}(x)|\text{sound})$, where $P(^{\Phi}(x))$ indicates a sound source of interest at a particular position x given a sound is detected. In some embodiments, the posterior likelihood estimator **832** may estimate the posterior likelihood **116** based on SSL performed by the sound source localization module **822**, as discussed elsewhere herein. In some further embodiments, the posterior likelihood estimator **832** may combine the SSL with an output from the speech recognition component **112** to estimate the posterior likelihood **116** as indicated by signal line **138** and the dotted line leading to block **116** in FIG. **1**.

The posterior likelihood estimator **832** may provide the posterior likelihood estimate **116** to the graphical representation module **834** (e.g., see FIG. **8**B) for it to generate an evidence grid representing the estimate. For example, FIG. **12**C depicts an evidence grid **1220** representing a posterior likelihood of a sound source estimated based on SSL. In the evidence grid **1220**, the black region indicates a highly likely sound source region while the white region indicates an unlikely sound source region. The white cross as indicated by reference numeral **1222** is used to indicate the actual sound source position while the grey cross as indicated by reference numeral **1224** is used to indicate an estimated position based on the posterior likelihood represented by the grid **1220**. By way of another example, FIG. **4** is a graphical representation illustrating a posterior likelihood estimate based on a set of time delay on arrival measurements from a capturing device (e.g., microphone array).

The posterior likelihood estimator **832** may estimate a posterior likelihood **118** ($P(^{\Phi}(x)|\text{gesture})$, where $P(^{\Phi}(x))$ indicates a sound source of interest at a particular position x given a user gesture, such as a pointing direction is detected. In some embodiments, the posterior likelihood estimator **832** may estimate the posterior likelihood **118** based on a user pointing direction and/or gesture identified by the gesture detection module **824**, as discussed elsewhere herein. In some further embodiments, the posterior likelihood estimator **832** may combine the user gesture (e.g., gesturing direction) with a user's body pose (e.g., the user's body position and/or orientation) to estimate the posterior likelihood **118** as indicated by signal lines **130** and **132** in FIG. **1**.

The posterior likelihood estimator **832** may provide the posterior likelihood estimate **118** to the graphical representation module **834** for it to generate an evidence grid representing the estimate. For example, FIG. **12**A depicts an evidence grid **1200** representing a posterior likelihood of a sound source estimated based on a user pointing gesture. In the evidence grid **1200**, the black region indicates a highly likely sound source region while the white region indicates an unlikely sound source region. The white cross as indicated by reference numeral **1204** is used to indicate the actual sound source position while the grey cross as indicated by reference numeral **1202** is used to indicate an estimated position based on the posterior likelihood represented by the grid **1200**. By way of another example, FIG. **5** is a graphical representation depicting a posterior likelihood estimate of a sound source based on a user pointing direction.

The posterior likelihood estimator **832** may estimate a posterior likelihood **120** ($P(^{\Phi}(x)|\text{speech})$, where $P(^{\Phi}(x))$ indicates a sound source of interest at a particular position x given a user speech is detected. In some embodiments, the posterior likelihood estimator **832** may estimate the posterior likelihood **120** based on a user speech segment recognized by the speech recognition module **826**, as discussed elsewhere herein. In further embodiments, the posterior likelihood estimator **832** may combine the user speech with a user's body pose (e.g., the user's body position and/or orientation) to estimate the posterior likelihood **120** as indicated by signal lines **134** and **136** in FIG. **1**.

The posterior likelihood estimator **832** may provide the posterior likelihood estimate **120** to the graphical representation module **834** for it to generate an evidence grid representing the estimate. For example, FIG. **12**B depicts an evidence grid **1210** representing the posterior likelihood of the sound source estimated based on a user speech. In the evidence grid **1210**, the black region indicates a highly likely sound source region while the white region indicates an unlikely sound source region. The white cross as indicated by reference numeral **1212** is used to indicate the actual sound source position while the grey cross as indicated by reference numeral **1214** is used to indicate an estimated position based on the posterior likelihood represented by the grid **1210**. By way of another example, FIG. **6** is a graphical representation depicting a posterior likelihood estimate of a sound source based on a user speech command indicating the direction "right". It should be understood that one or more combinations as discussed above for estimating the posterior likelihood **116**, **118**, and **120** are not limiting, and other combinations are also possible including, for example, estimating the posterior likelihood **118** based on combining outputs from the gesture detection **110**, speech recognition **112**, and body pose estimation **114** components, respectively.

In some embodiments, given a point of origin and an angle, Θ, the posterior likelihood estimator **832** may estimate a likelihood, L, using the following equation:

$$L(d\theta,\sigma)==K_1 e^{-0.5*(d\theta,\sigma)2}+K_0,$$

where dθ is the angular distance from an arbitrary point in space to the ray centered in the body, σ represents the standard deviation in pointing gesture accuracy, and K_1 and K_0 are constants limiting the range of maximum likelihood.

Fusion Layer **106**

In the fusion layer **106**, the fusion module **842** (e.g., see FIG. **8**D) may fuse posterior likelihood estimated in the synchronization layer **104** into an overall posterior likelihood **122**. In some embodiments, the fusion module **842** fuses the estimated posterior likelihoods by combining them together. In a further example, the fusion module **842** may first add the posterior likelihoods estimated based on user inputs (e.g., user gesture, user speech, user body pose, etc.) together into a combined posterior likelihood, scale or normalize the combined posterior likelihood to come in same range of the posterior likelihood estimated based on sound source location (SSL), and then add the scaled/normalized combined posterior likelihood to the posterior likelihood associated with SSL to estimate an overall posterior likelihood.

In some embodiments, the fusion module **842** may be directly coupled to the posterior likelihood estimator **832** to receive the posterior likelihoods **116**, **118**, and/or **120** and then combine them to determine the overall posterior likelihood **122**. The overall posterior likelihood **122** ($P(\Phi(x)|\text{sound, gesture, speech})$ may indicate an actual position **124** of the sound source of interest based on combining the posterior likelihoods estimated based on the sound source location (SSL), the user gesture, and/or the user speech.

In some embodiments, the fusion module **842** may provide the overall posterior likelihood **122** to the graphical representation module **834** for it to generate an evidence grid representing the overall likelihood. For example, FIG. **12**D depicts an overall evidence grid **1230** representing the overall posterior likelihood of the sound source estimated based on combining likelihoods associated with a user pointing gesture, user speech, and SSL. In this figure, the angles generated from user inputs and the SSL, when combined, effectively triangulate upon the source location. As shown, a small region of high likelihood is centered about the real source location. In some embodiments, the graphical representation module **834** may combine the evidence grids **1200**, **1210**, and **1220** to generate the overall evidence grid **1230**. In some embodiments, prior to combining, each evidence grid may first be scaled and/or normalized to a same range (because of different sampling rates associated with SSL **108**, gesture detection **110**, speech recognition **112**, etc.) and once each evidence grid is scaled to the same range, they may be combined together to generate the overall evidence grid **1230**. Ideally, fusing evidence grids created by the separate

In some embodiments, posterior likelihoods and/or evidence grids are combined or fused by adding, averaging, or otherwise mathematically compiling them together. However, in some embodiments, substantially different sampling rates may be used to detect inputs, and as a result, each grid may be normalized to the same range before they are fused together. For instance, each grid may be scaled to within [−3, 3] before they are combined together. In some embodiments, sound source locations may be extracted from the grid by thresholding the evidence grade, which may leave regions of high likelihood. These regions are then clustered to find the target location. As an example, in a scenario having one real sound source, the weighted centroid of the cluster with the greatest cumulative evidence may be selected as the target location.

In the evidence grid **1230**, the rounded black region indicates a highly likely sound source region while the white region indicates an unlikely sound source region. The white cross as indicated by reference numeral **1232** is used to indicate the actual sound source position while the grey cross as indicated by reference numeral **1234** is used to indicate an estimated position based on the overall posterior likelihood represented by the grid **1230**. As depicted, the overall posterior likelihood as represented by the grid **1230** is representative of an actual position that approximates the real position of the sound source. As an another example, FIG. **7** depicts a graphical representation of an overall posterior likelihood estimate of a sound source based on combining the SSL and user inputs.

In some embodiments, the overall posterior likelihood **122** and the overall evidence grid representing the overall posterior likelihood **122** can be passed on to the sound source investigator **844** (e.g., see FIG. **8**D) for further sound source analysis. In some embodiments, the overall evidence grid includes a narrowed auditory space (e.g., see FIG. **12**D) as compared to the original auditory space before estimating the overall posterior likelihood (e.g., see FIGS. **12**A-C), and the sound source investigator **844** may use this narrowed auditory space for investigating other objects of interest. In some embodiments, the sound source investigator **844** may use one or more perceptual object investigation algorithms **126** for performing this investigation. Performing further analysis or investigation on the narrowed auditory space is advantageous because (1) false positives may be reduced as search space is significantly narrowed, (2) processing may be reduced with the size of the search space, and (3) it does not overwhelm the user with uninteresting directions and the need to search the entire surrounding space.

Methods

FIG. **2** is a flowchart of an example method **200** for determining a position of a sound source of interest based on SSL and user inputs. In block **202**, one or more user inputs are received. In some embodiments, the one or more user inputs may include one or more of a user gesture, a user speech segment, and/or a user body pose, which may be detected by the gesture detection module **824**, the speech recognition module **826**, and/or the body pose estimation module **828**, respectively. In block **204**, one or more capturing devices may capture a sound associated with a sound source using SSL. A capturing device may include a microphone array, such as a video capture device (e.g., the video capture device **812**), an audio capture device (e.g., the audio capture device **814**), or an image capturing device (e.g., the image capture device **816**), as depicted in FIG. **8**A.

Upon receiving the one or more user inputs in block **202** and the localized sound in block **204**, the posterior likelihood estimator **832** may estimate **206** one or more first posterior likelihoods of one or more positions of the sound source based on the one or more user inputs and estimate **208** a second posterior likelihood of a position of the sound source based on the sound. In some embodiments, the posterior likelihood estimator **832** may provide the one or more first posterior likelihoods and the second posterior likelihood to the fusion module **842** for it to perform its acts and/or functionalities thereon.

The fusion module **842** may fuse **210** the one or more first posterior likelihoods estimated based on the one or more user inputs and the second posterior likelihood estimated based on the sound to determine an overall posterior likelihood. In block **212**, an estimate for an actual position of the sound source may be determined based on the overall posterior likelihood, as described elsewhere herein. In some embodiments, the operation in block **212** may be performed by the sound source investigator **844**.

FIG. **3**A-**3**E is a flowchart of an example method **300** for determining a position of a sound source of interest based on two or more inputs. In block **302**, one or more inputs are detected. The one or more inputs may be detected as one or more sound source locations (as shown in block **304**), a user body pose (as shown in block **306**), a user gesture (as shown in block **308**), and/or a user speech segment (as shown in block **310**). In some embodiments, the one or more inputs may be detected by one or more software and/or hardware components of the detection layer **102** as shown in FIG. **8**B. For instance, the one or more sound source locations may be detected by the sound source localization module **822**, the gesture may be detected by the gesture detection module **824**, the speech segment may be detected by the speech recognition module **826**, and/or the user body pose may be detected by the body pose estimation module **828**, etc.

If in block **304**, one or more sound source locations are detected then the sound source localization module **822** may identify **320** one or more probable sound source locations and provide them to the posterior likelihood estimator **832**, which may use them to estimate **322** a posterior likelihood of a position of the sound source. In some embodiments, the posterior likelihood estimator **832** may generate an evidence grid that graphically represents the posterior likelihood of a position of a sound source (e.g., see FIGS. **12**A-D) based on the one or more probable sound source locations. For instance, as shown in the method **390** of FIG. **3**G, the graphical representation module, in cooperation with the posterior likelihood estimator **832**, may generate **330** an evidence grid that graphically represents the posterior likelihood of a position of a sound source based on various inputs, such as one or more user inputs or sound source localization data. In various cases, the evidence grid may be provided for display **326** by the detector **810**.

Returning to FIG. **3**A, if in block **306**, a user body pose is detected then the body pose estimation module **828** may identify **330** the user's body pose. In some embodiments, a body pose may include the user's body position and/or orientation relative to one or more capturing devices). In some embodiments, the body pose may be used with other inputs to generate various posterior likelihood estimates, as discussed elsewhere herein. In other embodiments, the body pose may be provided to the posterior likelihood estimator **832**, which may use it to estimate **332** a posterior likelihood of a position of the sound source. In some embodiments, the graphical representation module **834** may generate an evidence grid reflecting the posterior likelihood estimated based on the user's body pose, as discussed elsewhere herein.

If in block **308**, a user gesture is detected then the gesture detection module **824** may identify **340** a direction in which the user is gesturing (e.g., pointing) and then provide the gesturing direction to the posterior likelihood estimator **832** to estimate a posterior likelihood. In block **342**, the body pose estimation module **828** determines whether a user's body pose is available, and if so, the posterior likelihood estimator **832** receives **344** the user body pose including the user body position and/or orientation from the body pose estimation module **828** and/or a memory and estimates **346** a gesture-pose-based posterior likelihood of a position of the sound source based on a combination of gesturing direction and the user's body pose. If the determination in block **342** is negative, then the posterior likelihood estimator **832** may estimate **348** a posterior likelihood of a position of the sound source based on the gesturing direction. In some embodiments, the graphical representation module **834** may generate an evidence grid reflecting the gesture-based posterior likelihood and/or the gesture-pose-based posterior likelihood, as discussed elsewhere herein.

If in block **310**, a user speech segment is detected then the speech recognition module **826** may recognize **360** the user speech segment and determine **362** a direction from the speech segment. For example, a user has asked about a particular sound by using a speech segment "what's that sound on the right?" and the speech recognition module **826** may recognize this speech segment and determine the direction "right" from the segment. In block **364**, a determination is made as whether user body pose is available. If the result of the determination is affirmative, then the posterior likelihood estimator **832** may receive **366** the user's body pose and estimate **368** a speech-pose-based posterior likelihood of a position of the sound source based on a combination of a direction associated with the user speech segment and the user's body pose. If on the other hand the result of the determination in block **342** is negative, then the posterior likelihood estimator **832** may estimate **370** a posterior likelihood of a position of the sound source based on the direction associated with the user speech segment. In some embodiments, the graphical representation module **834** may generate an evidence grid reflecting the speech-based posterior likelihood and/or the speech-pose-based posterior likelihood, as discussed elsewhere herein.

Next, then the method **300** may determine whether to receive **312** more inputs. If the result of the determination in block **312** is affirmative, then the method **300** may return to block **302** to detect additional inputs. Otherwise, the method **300** continues to block **380** where the fusion module **842** may receive, from the posterior likelihood estimator **832**, the posterior likelihood estimated based on the one or more probable sound source location and one or more posterior likelihoods estimated based on one or more user inputs including the user gesture, the user speech segment, and/or the user body pose.

In some embodiments, a determination is made in block **382** as whether two or more posterior likelihoods are estimated based on two or more user inputs. If the result of the determination in block **382** is affirmative, then the fusion module **842** may combine **384** the two or more posterior likelihoods into a combined posterior likelihood, scale and/or normalize **386** the combined posterior likelihood, and then fuse **388** the scaled combined posterior likelihood and the posterior likelihood estimated based on SSL to determine an overall posterior likelihood. If on the other hand, the result of the determination in block **382** is negative, then the fusion module **842** may combine **390** the posterior likelihood estimated based on the SSL and a posterior likelihood estimated based on the relevant user input to determine an overall posterior likelihood. In block **392**, an estimation of the actual position of the sound source is determined based on the overall posterior likelihood. In some embodiments, the estimation of the actual position may be determined by determining a position that maximizes the overall posterior likelihood. The estimated actual position may then be used to guide **394** a mobile computing device (e.g., robot) to the sound source.

System Architecture

As depicted in FIG. **8**A, the technology described herein may include a system **800** having a computing device **801**. The system **800** also includes a server **852** hosting an application **854**. Each of the entities **801** and/or **852** may be coupled to a network **850** for cooperation and electronic communication with one another. The architecture illustrated in FIG. **8**A is provided by way of non-limiting example and it should be understood that numerous other configurations are possible and contemplated. For example, any number of computing devices **801** and/or servers **852** may be included in the system **800** and coupled to the network **850**.

The network **850** can be a conventional type, wired or wireless, and may have numerous different configurations including a star configuration, token ring configuration, or other configurations. Furthermore, the network **850** may include one or more local area networks (LAN), wide area networks (WAN) (e.g., the Internet), public networks, private networks, virtual networks, and/or other interconnected data paths across which multiple devices may communicate. In some embodiments, the network **850** may be a peer-to-peer network. The network **850** may also be coupled to or includes portions of a telecommunications network for sending data in a variety of different communication protocols. In some embodiments, the network **850** includes Bluetooth communication networks or a cellular communications network for sending and receiving data including via short messaging service (SMS), multimedia messaging service (MMS), hypertext transfer protocol (HTTP), direct data connection, WAP, email, etc. Although FIG. **1** illustrates one network **850** coupled to the computing device **801** and the server **852**, in practice one or more networks **850** can be connected to these entities.

The computing device **801** is any device having data processing and communication capabilities. The computing device **801** may couple to and communicate with one another and the other entities of the system **800** via the network **850** using a wireless and/or wired connection. As depicted in FIG. **8**A, the computing device **801** may include a processor **802**, a memory **804**, a communication unit **808**, a detector **810**, a video capture device **812**, an audio capture device **814**, an image capture device **816**, and a communication bus **806** that couples its constituent hardware components for communication/signaling purposes. However, it should be understood that the computing device **801** is not limited to the components illustrated in the computing device **801**, and may include one or more other components including for example, a power source (e.g., battery), a GPS receiver; a Bluetooth® module, sensors (e.g., accelerometers, gyroscopes, thermocouples), graphics processor, firmware, operating systems for managing the hardware and resources of the computing device **801**, drivers, various physical connection interfaces (e.g., USB, HDMI, etc.), etc. Non-limiting examples of a computing device **801** include a robot, smartphone, a tablet computer, a laptop computer, a netbook computer, a desktop computer (e.g., equipped with a touchscreen), a vehicle with an on-board computing device, a computing surface (e.g., a computer-enabled countertop, a tabletop, a wall, etc.), and/or any other computing devices capable of providing similar acts and/or functionality.

The processor **802** can include one or more processing units, such as an arithmetic logic unit, a microprocessor, a general purpose controller, a specialized processing unit, or some other processor array to perform computations and provide electronic display signals to a display device (not shown). The processor **802** can process data signals and may include various computing architectures including a complex instruction set computer (CISC) architecture, a reduced instruction set computer (RISC) architecture, an architecture implementing a combination of instruction sets, etc. In some embodiments, the processor **802** may include one or more general processors, special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like. Although FIG. **8**A depicts a single processor **802**, multiple processors **802** may be included. Other processors, operating systems, sensors, displays and physical configurations are possible.

The memory **804** can include one or more non-transitory computer-readable media for storing instructions and/or data that can be executed by the processor **802**. The instructions and/or data may include code for performing the techniques described herein. In some embodiments, the memory **804** may store the detector **810**. The memory **804** may include a dynamic random access memory (DRAM) device, a static random access memory (SRAM) device, embedded memory, flash memory, or some other memory device. In some embodiments, the memory **804** can also include a non-volatile memory or similar permanent storage device and media including a hard disk drive, a floppy disk drive, a CD-ROM device, a DVD-ROM device, a DVD-RAM device, a DVD-RW device, a flash memory device, or some other mass storage device for storing information on a more permanent basis.

The communication unit **808** can transmit and receive data to and from the server **852** and/or the computing device **801**. The communication unit **808** may be coupled (wiredly, wirelessly, etc.) to the network **850** to communicate with other entities forming the network **850**. In some embodiments, the communication unit **808** may include one or more ports for direct physical connection to the network **850** or to another communication channel. For example, the communication unit **808** may include a USB, SD, CAT-5 or similar port for wired communication with the server **852** and/or the computing device **801**. In some embodiments, the communication unit **808** may include a wireless transceiver for exchanging data with the server **852** or other communication channels using one or more wireless communication methods, including IEEE 802.11, IEEE 802.16, BLUETOOTH®, dedicated short-range communications (DSRC) or another suitable wireless communication method.

In some embodiments, the communication unit **808** can include a cellular communications transceiver for sending and receiving data over a cellular communications network including via short messaging service (SMS), multimedia messaging service (MMS), hypertext transfer protocol (HTTP), direct data connection, WAP, e-mail or another suitable type of electronic communication. In some embodiments, the communication unit **808** can include a wired port and a wireless transceiver. The communication unit **808** can also provide other conventional connections to the network **850** for distribution of files and/or media objects using standard network protocols including TCP/IP, HTTP, HTTPS, and SMTP, etc.

The video capture device **812** is any device capable of capturing one or more moving visual images and converting them into a format such that they appear to be continuous to a user. Non-limiting examples of the video capture device **812** may include a video recorder, a camcorder, a webcam, a camera, etc. The audio capture device **812** is any device capable of capturing one or more audible components including, for example, a user speech, a voice command, a song, or any other sound effect. Non-limiting examples of the audio capture device **814** may include a microphone, a sensor, or the like. The image capture device **816** is any device capable of capturing one or more still images in its surrounding environment. Non-limiting examples of the image capture device **816** may include a webcam, a camera, a sensor, etc. The one or more capturing devices referred to herein may include in various embodiments one or more of the video capture device **812**, the audio capture device **812**, and the image capture device **816**.

The detector **810** may detect a sound source of interest at its accurate location in a shared auditory space and guide a mobile computing device, such as a robot to the sound source of interest using the location. As depicted, the detector **810** may include the detector layer **102**, the synchronization layer **104**, and the fusion layer **106** as described above with respect to FIG. **1**. As depicted, the detector **810** is shown with dashed lines to indicate that the detector **810** is not an integral part of the computing device **801** and that it may be included in other entities connected to the network **850**. For instance, an instance of the detector **810** may be included in the server **852**, which may include on or more of the components and/or be configured to perform one or more of the acts and/or functionalities of the detector **810**.

The server **852** may include one or more computing devices having data processing, storing, and communication capabilities. For example, the server **852** may include one or more hardware servers, server arrays, storage devices and/or systems, etc. In some embodiments, the server **852** may include one or more virtual servers, which operate in a host server environment and access the physical hardware of the host server including, for example, a processor, memory, storage, network interfaces, etc., via an abstraction layer (e.g., a virtual machine manager).

In the depicted illustration, the server **852** include an application **854** operable to provide various computing functionalities, services, and/or resources, and to send data to and receive data from the other entities of the network **850**, such as the computing device **801**. For example, the application **854** may provide functionality for user account management, internet searching; social networking; web-based email; word-processing; banking; finance; blogging; micro-blogging; photo management; video, music and multimedia hosting, distribution, and sharing; business services; news and media distribution; any combination of the foregoing services; etc. It should be understood that the server **852** is not limited to providing the above-noted services and may include other network-accessible service.

The application **854** may transmit electronic files and/or data embodying the services it provides to the computing device **801** for rendering. In some implementations, the electronic files and/or data streams may be formatted using a markup language(s) or other processing (e.g., HTML, XML, JSON, etc.), style sheet(s) (e.g., CSS, XSL, etc.), graphic(s) (e.g., PNG, JPG, GIF, etc.), and/or scripts (e.g., JavaScript, ActionScript, etc.), and the computing device **801** may interpret and/or execute processes in association with the electronic files and/or data streams and/or render an interactive Web User Interface (WUI) for presentation to a user based on the electronic files and/or data streams.

FIGS. **8**B-**8**D illustrates various software components that are associated with the detection layer **102**, the synchronization layer **104**, and the fusion layer **106**, respectively. In particular, the detection layer **102** (as depicted in FIG. **8**B) includes a sound source localization module **822**, a gesture detection module **824**, a speech recognition module **826**, and a body pose estimation module **828**. The synchronization layer **104** (as depicted in FIG. **8**C) includes a posterior likelihood estimator **832** and a graphical representation module **834**. The fusion layer **106** (as depicted in FIG. **8**D) includes a fusion module **842** and a sound source investigator **844**. These components **822**, **824**, **826**, **828**, **832**, **834**, **842**, and/or **844** are described in detail with respect to at least FIG. **1** and methods **200** and **300**, and hence the description for these components will not be repeated here.

The components **822**, **824**, **826**, **828**, **832**, **834**, **842**, and/or **844** may be communicatively coupled by the bus **806** and/or the processor **802** to one another and/or the other components **804**, **808**, **812**, **814**, and/or **816** of the computing device **801**. In some embodiments, one or more of the components **822**, **824**, **826**, **828**, **832**, **834**, **842**, and/or **844** are sets of instructions executable by the processor **802** to provide their functionality. In other embodiments, one or more of the components **822**, **824**, **826**, **828**, **832**, **834**, **842**, and/or **844** are stored in the memory **804** of the computing device **801** and are accessible and executable by the processor **802** to provide their functionality. In any of the foregoing embodiments, these components **822**, **824**, **826**, **828**, **832**, **834**, **842**, and/or **844** may be adapted for cooperation and communication with the processor **802**, other components of the computing device **801**, and/or the server **852**. In various embodiments, these components may be implemented via software, hardware, firmware, a combination of the foregoing, etc.

Example Scenarios

Scenario 1 illustrates the effectiveness of combining speech, pointing, and computational SSL components for sound source detection. In this scenario, a single loud source (60 dB) was used in a shared auditory environment. FIG. **13** summarizes angular localization error associated position determined based on SSL alone, and position determined based on combining speech and pointing likelihoods first, scaling the combined likelihoods, and adding the scaled combined likelihoods (referring in figure to as Human) to the SSL component. Advantageously, as depicted, using the SSL alone had an average error of approximately 0.13 (rad) while using the combined likelihoods plus the SSL likelihood had an error of only 0.09 (rad), an improvement of 0.04 (rad) over SSL alone.

Scenario 2 further illustrates the effectiveness of combining speech, pointing, and computational SSL components for sound source detection in comparison to detecting the sound source using each of these components individually. In this scenario, multiple sound sources were used in a shared auditory environment. FIG. **14**A depicts sound source location estimated using computational SSL alone. In this figure, a star represents a correct sound source location and a diamond represents a location estimated using SSL. As shown, the computational SSL alone is not effective for determining the position of the sound source in a multiple sound source environment. In contrast, FIG. **14**B depicts that combining pointing and speech with the computational SSL as described herein is an effective approach for determining the position of the sound source in a multiple sound source environment.

In the above description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the specification. It should be understood, however, that the disclosure can be practiced without these specific details. In some embodiments, structures and devices are shown in block diagram form in order to avoid obscuring the description. For example, various embodiments are described primarily with reference to user interfaces and particular hardware. However, the embodiments apply to any type of computing device that can receive data and commands, and any peripheral devices providing services.

Reference in the specification to "an embodiment" or "some embodiments" means that a particular feature, structure, or characteristic described in connection with the embodiment(s) is included in at least one embodiment of the description. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment.

Some portions of the detailed descriptions that follow are presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like.

It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms including "processing" or "computing" or "calculating" or "determining" or "displaying" or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

The specification also relates to an apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may comprise a general-purpose computer selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a computer readable storage medium, including, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, and magnetic disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, magnetic or optical cards, flash memories including USB keys with non-volatile memory or any type of media suitable for storing electronic instructions, each coupled to a computer system bus.

The specification can take the form of an entirely hardware embodiment, an entirely software embodiment or an embodiment containing both hardware and software elements. In a preferred embodiment, the specification is implemented in software, which includes but is not limited to firmware, resident software, microcode, etc.

Furthermore, the description can take the form of a computer program product accessible from a computer-usable or computer-readable medium providing program code for use by or in connection with a computer or any instruction execution system. For the purposes of this description, a computer-usable or computer readable medium can be any apparatus that can contain, store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device.

A data processing system suitable for storing and/or executing program code will include at least one processor coupled directly or indirectly to memory elements through a system bus. The memory elements can include local memory employed during actual execution of the program code, bulk storage, and cache memories which provide temporary storage of at least some program code in order to reduce the number of times code must be retrieved from bulk storage during execution.

Input/output or I/O devices (including but not limited to keyboards, displays, pointing devices, etc.) can be coupled to the system either directly or through intervening I/O controllers.

Network adapters may also be coupled to the system to enable the data processing system to become coupled to other data processing systems or remote printers or storage devices through intervening private or public networks. Modems, cable modem and Ethernet cards are just a few of the currently available types of network adapters.

Finally, the algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general-purpose systems may be used with programs in accordance with the teachings herein, or it may prove convenient to construct more specialized apparatus to perform the required method steps. The required structure for a variety of these systems will appear from the description below. In addition, the specification is not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the specification as described herein.

The foregoing description has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the specification to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the disclosure be limited not by this detailed description, but rather by the claims of this application. As will be understood by those familiar with the art, the specification may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. Likewise, the particular naming and division of the modules, routines, features, attributes, methodologies and other aspects are not mandatory or significant, and the mechanisms that implement the specification or its features may have different names, divisions and/or formats. Furthermore, as will be apparent to one of ordinary skill in the relevant art, the modules, routines, features, attributes, methodologies and other aspects of the disclosure can be implemented as software, hardware, firmware or any combination of the three. Also, wherever a component, an example of which is a module, of the specification is implemented as software, the component can be implemented as a standalone program, as part of a larger program, as a plurality of separate programs, as a statically or dynamically linked library, as a kernel loadable module, as a device driver, and/or in every and any other way known now or in the future to those of ordinary skill in the art of computer programming. Additionally, the disclosure is in no way limited to implementation in any specific programming language, or for any specific operating system or environment. Accordingly, the disclosure is intended to be illustrative, but not limiting, of the scope of the subject matter set forth in the following claims.

What is claimed is:

1. A computer-implemented method comprising:
- receiving, using one or more computing devices, one or more user inputs;
- capturing, using the one or more computing devices, a sound associated with a sound source via one or more capturing devices using sound source localization;
- estimating, using the one or more computing devices, one or more first posterior likelihoods of one or more positions of the sound source based on the one or more user inputs;
- estimating, using the one or more computing devices, a second posterior likelihood of a position of the sound source based on the sound; and
- estimating, using the one or more computing devices, an overall posterior likelihood of an actual position of the sound source based on 1) the one or more first posterior likelihoods of the one or more positions of the sound source estimated based on the one or more user inputs and 2) the second posterior likelihood of the position of the sound source estimated based on the sound.

2. The computer-implemented method of claim **1**, wherein estimating the overall posterior likelihood further includes:
- fusing, using the one or more computing devices, the one or more first posterior likelihoods of the one or more positions of the sound source and the second posterior likelihood of the position of the sound source to produce the overall posterior likelihood.

3. The computer-implemented method of claim **2**, wherein the one or more first posterior likelihoods include two or more posterior likelihoods estimated based on two or more user inputs, and fusing the two or more first posterior likelihoods and the second posterior likelihood includes:
- combining, using the one or more computing devices, the two or more first posterior likelihoods into a combined posterior likelihood;
- scaling, using the one or more computing devices, the combined posterior likelihood; and
- combining the scaled combined posterior likelihood with the second posterior likelihood.

4. The computer-implemented method of claim **1**, wherein the one or more user inputs include one or more of a user gesture, a user speech segment, and a user body pose.

5. The computer-implemented method of claim **1**, wherein the one or more user inputs include a user gesture and a user body pose,

receiving the one or more user inputs further includes determining a gesturing direction from the user gesture and determining one or more of a position and orientation from the user body pose, and

estimating the one or more first posterior likelihoods further includes estimating a gesture-pose-based posterior likelihood of a position of the sound source based on the gesturing direction and the one or more of the position and orientation associated with the user body pose.

6. The computer-implemented method of claim **1**, wherein the one or more inputs include a user speech segment and a user body pose;

receiving the one or more user inputs further includes determining a direction from the user speech segment and determining one or more of a position and orientation from the user body pose, and

estimating the one or more first posterior likelihoods further includes estimating a speech-pose-based posterior likelihood of a position of the sound source based on the direction associated with the speech segment and the one or more of the position and orientation associated with the user body pose.

7. The computer-implemented method of claim **1**, wherein estimating the one or more first posterior likelihoods further includes generating one or more first evidence grids of likely sound source positions based on the one or more user inputs, the one or more first evidence grids reflecting the one or more first posterior likelihoods, respectively,

estimating the second posterior likelihood further includes generating a second evidence grid of likely sound source positions based on the sound, the second evidence grid reflecting the second posterior likelihood, and

estimating the overall posterior likelihood of the actual position of the sound source further includes combining the one or more first evidence grids and the second evidence grid.

8. The computer-implemented method of claim **1**, further comprising:

guiding, using the one or more computing devices, a mobile computing device to the actual position of the sound source.

9. The computer-implemented method of claim **1**, wherein the one or more capturing devices includes one or more of an image capturing device, a video capturing device, and an audio capturing device.

10. A computer program product comprising a non-transitory computer-readable medium storing a computer-readable program, wherein the computer-readable program, when executed on one or more computing devices, causes the one or more computing devices to:

receive one or more user inputs;

capture a sound associated with a sound source via one or more capturing devices using sound source localization;

estimate one or more first posterior likelihoods of one or more positions of the sound source based on the one or more user inputs;

estimate a second posterior likelihood of a position of the sound source based on the sound; and

estimate an overall posterior likelihood of an actual position of the sound source based on 1) the one or more first posterior likelihoods of the one or more positions of the sound source estimated based on the one or more user inputs and 2) the second posterior likelihood of the position of the sound source estimated based on the sound.

11. The computer program product of claim **10**, wherein to estimate the overall posterior likelihood further includes:

fusing the one or more first posterior likelihoods of the one or more positions of the sound source and the second posterior likelihood of the position of the sound source to produce the overall posterior likelihood.

12. The computer program product of claim **11**, wherein the one or more first posterior likelihoods include two or more posterior likelihoods estimated based on two or more user inputs, and to fuse the two or more first posterior likelihoods and the second posterior likelihood includes:

combining the two or more first posterior likelihoods into a combined posterior likelihood;

scaling the combined posterior likelihood; and

combining the scaled combined posterior likelihood with the second posterior likelihood.

13. The computer program product of claim **10**, wherein the one or more user inputs include one or more of a user gesture, a user speech segment, and a user body pose.

14. The computer program product of claim **10**, wherein the one or more user inputs include a user gesture and a user body pose,

to receive the one or more user inputs further includes determining a gesturing direction from the user gesture and determining one or more of a position and orientation from the user body pose, and

to estimate the one or more first posterior likelihoods further includes estimating a gesture-pose-based posterior likelihood of a position of the sound source based on the gesturing direction and the one or more of the position and orientation associated with the user body pose.

15. The computer program product of claim **10**, wherein the one or more inputs include a user speech segment and a user body pose;

to receive the one or more user inputs further includes determining a direction from the user speech segment and determining one or more of a position and orientation from the user body pose, and

to estimate the one or more first posterior likelihoods further includes estimating a speech-pose-based posterior likelihood of a position of the sound source based on the direction associated with the speech segment and the one or more of the position and orientation associated with the user body pose.

16. The computer program product of claim **10**, wherein to estimate the one or more first posterior likelihoods further includes generating one or more first evidence grids of likely sound source positions based on the one or more user inputs, the one or more first evidence grids reflecting the one or more first posterior likelihoods, respectively,

to estimate the second posterior likelihood further includes generating a second evidence grid of likely sound source positions based on the sound, the second evidence grid reflecting the second posterior likelihood, and

to estimate the overall posterior likelihood of the actual position of the sound source further includes combining the one or more first evidence grids and second evidence grid.

17. The computer program product of claim **10**, wherein the computer-readable program, when executed on the one or more computing devices, causes the one or more computing devices to:

guide a mobile computing device to the actual position of the sound source.

18. The computer program product of claim 10, wherein the one or more capturing devices includes one or more of an image capturing device, a video capturing device, and an audio capturing device.

19. A system comprising:

one or more processors; and

one or more memories storing instructions that, when executed by the one or more processors, cause the system to:

receive one or more user inputs;

capture a sound associated with a sound source via one or more capturing devices using sound source localization;

estimate one or more first posterior likelihoods of one or more positions of the sound source based on the one or more user inputs;

estimate a second posterior likelihood of a position of the sound source based on the sound; and

estimate an overall posterior likelihood of an actual position of the sound source based on 1) the one or more first posterior likelihoods of the one or more positions of the sound source estimated based on the one or more user inputs and 2) the second posterior likelihood of the position of the sound source estimated based on the sound.

20. The system of claim 19, wherein to estimate the overall posterior likelihood further includes:

fusing the one or more first posterior likelihoods of the one or more positions of the sound source and the second posterior likelihood of the position of the sound source to produce the overall posterior likelihood.

21. The system of claim 20, wherein the one or more first posterior likelihoods include two or more posterior likelihoods estimated based on two or more user inputs, and to fuse the two or more first posterior likelihoods and the second posterior likelihood includes:

combining the two or more first posterior likelihoods into a combined posterior likelihood;

scaling the combined posterior likelihood; and

combining the scaled combined posterior likelihood with the second posterior likelihood.

22. The system of claim 19, wherein the one or more user inputs include one or more of a user gesture, a user speech segment, and a user body pose.

23. The system of claim 19, wherein

the one or more user inputs include a user gesture and a user body pose,

to receive the one or more user inputs further includes determining a gesturing direction from the user gesture and determining one or more of a position and orientation from the user body pose, and

to estimate the one or more first posterior likelihoods further includes estimating a gesture-pose-based posterior likelihood of a position of the sound source based on the gesturing direction and the one or more of the position and orientation associated with the user body pose.

24. The system of claim 19, wherein

the one or more inputs include a user speech segment and a user body pose;

to receive the one or more user inputs further includes determining a direction from the user speech segment and determining one or more of a position and orientation from the user body pose, and

to estimate the one or more first posterior likelihoods further includes estimating a speech-pose-based posterior likelihood of a position of the sound source based on the direction associated with the speech segment and the one or more of the position and orientation associated with the user body pose.

25. The system of claim 19, wherein

to estimate the one or more first posterior likelihoods further includes generating one or more first evidence grids of likely sound source positions based on the one or more user inputs, the one or more first evidence grids reflecting the one or more first posterior likelihoods, respectively,

to estimate the second posterior likelihood further includes generating a second evidence grid of likely sound source positions based on the sound, the second evidence grid reflecting the second posterior likelihood, and

to estimate the overall posterior likelihood of the actual position of the sound source further includes combining the one or more first evidence grids and the second evidence grid.

26. The system of claim 19, wherein the computer-readable program, when executed on the one or more computing devices, causes the one or more computing devices to:

guide a mobile computing device to the actual position of the sound source.

27. The system of claim 19, wherein the one or more capturing devices includes one or more of an image capturing device, a video capturing device, and an audio capturing device.

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